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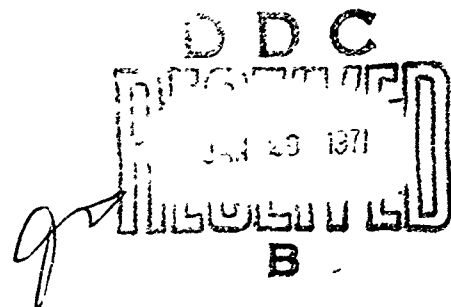# RESEARCH ON FLIGHT CONTROL SYSTEMS

VOLUME III, FLY-BY-WIRE TECHNIQUES

DALE G. BAZILL

GAVIN D. JENNEY

HYDRAULIC RESEARCH AND MANUFACTURING COMPANY

VALENCIA, CALIFORNIA

TECHNICAL REPORT AFFDL-TR-69-119, VOLUME III

OCTOBER 1970

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RESEARCH ON FLIGHT CONTROL SYSTEMS

VOLUME III, FLY-BY-WIRE TECHNIQUES

DALE G. BAZILL

GAVIN D. JENNEY

FOREWORD

The effort described in this document was performed
by the Controls Division of Hydraulic Research and Manu-
facturing Company, 25200 West Rye Canyon Road, Valencia,
California, under Air Force Contract F33615-68-C-1638
(Project 8225). Work under the contract was carried out
at Wright-Patterson Air Force Base utilizing United States
Air Force facilities. The program was monitored by
Mr. V. R. Schmitt and Mr. P. Blatt, Air Force Flight
Dynamics Laboratory (FDCL), Wright-Patterson Air Force
Base, Ohio 45433.

The authors wish to acknowledge the contributions
of Messers W. Stoddard, H. Schreadley, C. Black, and
W. Talley for their assistance in the preparation and
testing of the various Fly-By-Wire systems and associa-
ted research tasks.

The report covers work performed between 17 August
1968 and 14 November 1969. The report was released by
the authors in November 1969.

This technical report has been reviewed and is
approved.

H.W. Basham
Chief, Control Elements Branch
Flight Control Division
Air Force Flight Dynamics Laboratory

ABSTRACT

This report presents the results of an evaluation
of the operational characteristics of the flight control
systems and mechanizations that are permanently located
in the Hydraulics Laboratory of the Control Elements
Branch of the Air Force Flight Dynamics Laboratory in
Building 195, Wright-Patterson Air Force Base, Dayton,
Ohio. This effort was performed by Hydraulic Research
and Manufacturing Company personnel under Air Force Con-
tract F33615-68-C-1638.

The flight control systems evaluated were the Sperry
three axis, two-fail-operate Fly-By-Wire (FBW) system and
the McDonnell Douglas single axis, single-fail operate sys-
tem. The mechanizations evaluated were the Hydraulic Research
and Manufacturing Company's Polaris integrated actuator, the
Vickers Model MPEV3-044-2 motorpump, and the FDCL developed
hydrologic hydraulic power switching valve. In addition,
a discussion of redundant actuation and control equipment
design techniques is included in section three of this
volume.

The investigation disclosed that the Sperry and
McDonnell Douglas FBW systems have adequate dynamic res-
ponse and reasonable control transfer characteristics for
near future FBW applications. However, considerable re-
furbishing and redesign would be necessary to qualify the
mechanizations for actual flight test.

The Hydraulic Research and Manufacturing Company
Polaris integrated actuator was found to have adequate
performance for FBW applications, but considerable re-
furbishing and redesign would be necessary to extend the
operational life of this integrated actuator concept.

The Vickers motorpump has adequate performance for
consideration as a back up source for emergency hydraulic
power applications, but the suggested application guide-
lines listed in this report should be applied.

TABLE OF CONTENTS

iv

TABLE OF CONTENTS (cont)

TABLE OF CONTENTS (cont)

vi

TABLE OF CONTENTS (cont)

vii

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (cont)

LIST OF ILLUSTRATIONS (cont)

LIST OF ILLUSTRATIONS (cont)

LIST OF ABBREVIATIONS

AC	Alternating Current
Amp	Amplifier
A/R	Amplitude Ratio
^{o}C	Degrees Centigrade
(cont)	Continued
db	Decibel
DC	Direct Current
Def.	Deflection
Div.	Division
^{o}F	Degrees Fahrenheit
F-4	Aircraft Type
FBW	Fly-By-Wire
FDCL	Control Elements Branch, Air Force Flight Dynamics Laboratory
Fig.	Figure
Fig. No.	Figure Number
F/M	Flow Meter
Gal.	Gallon
GPM	Gallons per Minute
HP	Horsepower
H_z	Cycles per Second
in^2	Inches Squared
in/sec	Inches per Second
KH_z	1000 Cycles per Second
LVDT	Linear Variable Differential Transformer
MA	Milliamp
N_n	Acceleration Feedback
psi	Pounds per Square Inch
P-Q	Pressure - Flow
Ref. Sig.	Reference Signal
Res	Reservoir
RMS	Root Mean Square
RVDT	Rotary Variable Differential Transformer
Secs.	Seconds
Sq. Wave	Square Wave
TC	Thermocouple
VAC	Volts Alternating Current
vs	Versus
$\dot{\theta}$	Pitch Rate
δe	Elevator Position
%	Percent
θ	Phase

SECTION I

INTRODUCTION

This section of this report describes the mechanizations, test procedures, and results obtained of an experimental study of servo actuators and associated components supplied as facility items during the period of this contract. The purpose of this investigation was to determine those characteristics of the system or component evaluated which make the mechanization or item more or less desirable for use in future Fly-By-Wire flight control systems.

The systems and components evaluated during this effort were the Sperry two-fail operate Fly-By-Wire (FBW) system, the McDonald Douglas single-fail operate FBW system, the Hydraulic Research and Manufacturing Company Polaris integrated pakcage servo actuator and the Vickers Model MPEV3-044-2 Motor Pump Assembly.

1

EXPERIMENTAL STUDIES ON SERVOACTUATORS

1. SPERRY FLY-BY-WIRE SYSTEM

1.1 Introduction

The Sperry Fly-By-Wire (FBW) system is a three axis, two-fail operate mechanization composed of channel electronics, control simulator, sidearm controller and electrohydraulic servoactuator. These units are shown in Fig. 1.

The Sperry FBW system was designed as an experimental laboratory model demonstrator of a particular FBW design technique applied to a Boeing B-47 aircraft flight control system. However, the packaging of the channel electronics and servoactuator was arranged to allow the system to be installed in a B-47 aircraft for flight test evaluation.

The Sperry FBW system was developed under contract F33 615-67-C-1510 (Ref. 1) and was a continuation of the research conducted by Sperry under contract AF 33(516)-3615 (Ref. 2) on Fly-By-Wire flight control systems. The Sperry FBW system was completed in August 1968.

1.2 General System Description

The Sperry FBW system demonstrator provided three control axes for evaluation. The pitch axis was complete, incorporating the necessary electrohydraulic actuator in hardware form. For the roll and yaw axis mechanization, the electrohydraulic actuator was modelled electrically.

Fig. 2 is a block diagram of the pitch (longitudinal) axis. The pilot's input, modified by pitch rate ($\dot{\theta}$) and normal acceleration (N_n) feedback, controlled the output of the electrohydraulic servoactuator. A position transducer attached to the actuator develops a signal proportional to elevator position (δe). This signal proportional to δe was fed to an aircraft analog model which developed the N_n and θ feedback signals.

ELECTROHYDRAULIC SERVOACTUATOR

CONTROL SIMULATOR

SIDE ARM CONTROLLER

CHANNEL ELECTRONICS

5070-1
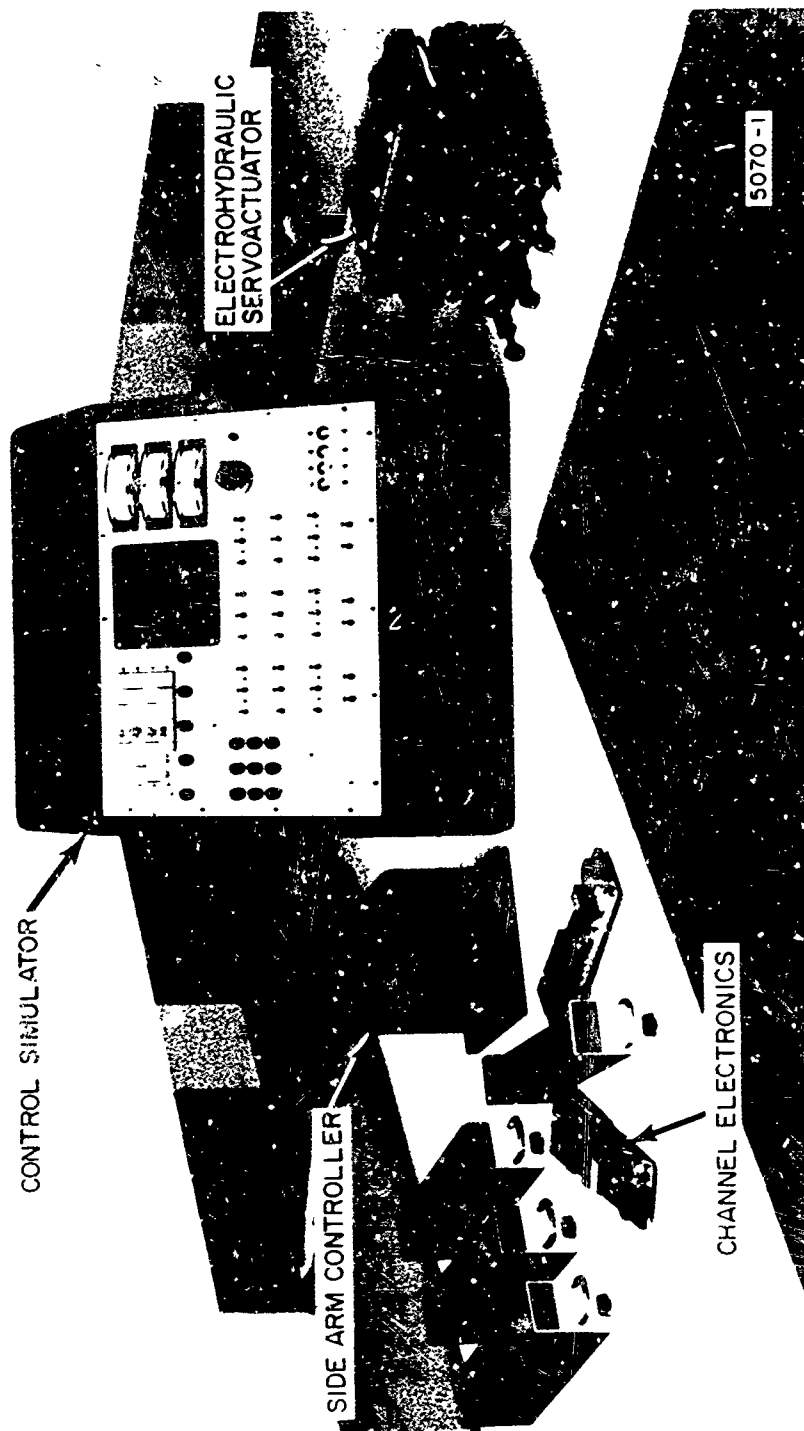
Figure 1. Fly-By-Wire Flight Control System Units

3
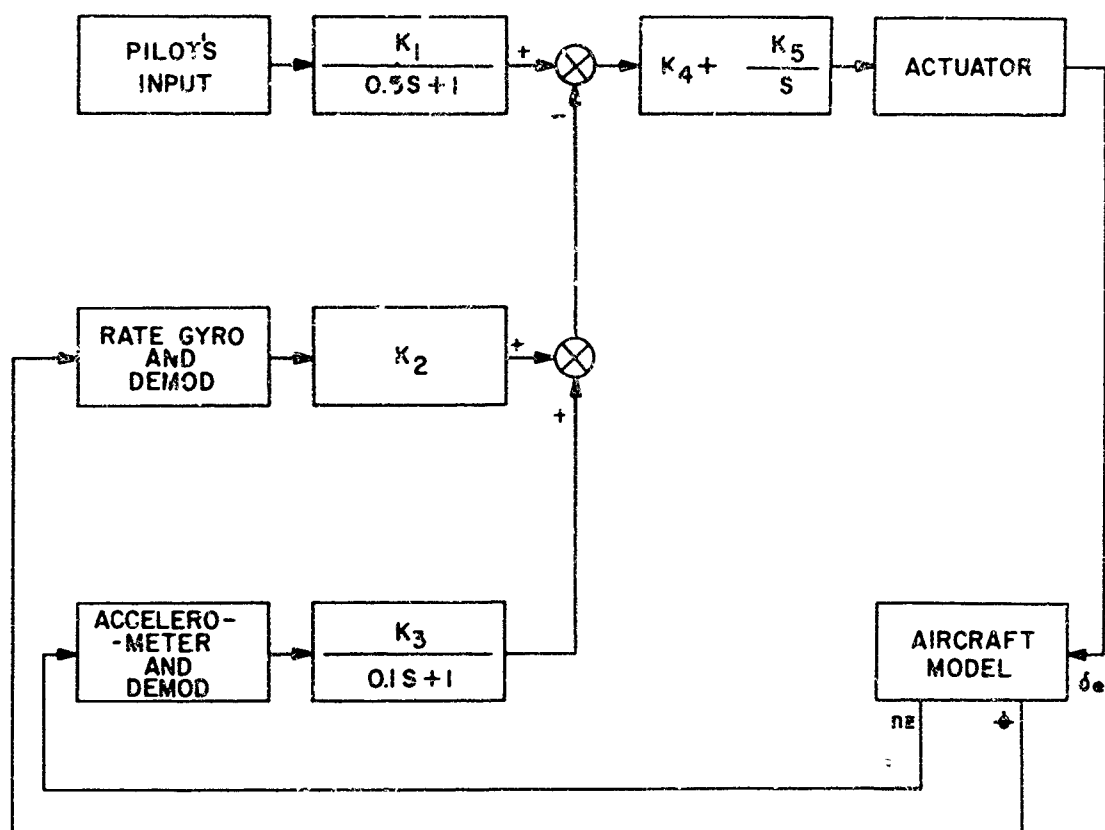
Figure 2. Longitudinal Axis Block Diagram

4

The block diagram of the roll and yaw lateral direction axes as shown in Fig. 3. The pilot's roll or yaw inputs are modified by roll and yaw rate feedback and applied to analog models of the roll and yaw actuators. The actuator models generate a surface response signal which is modified by the analog simulation of the aircraft dynamics and demodulator and scaled to yield the desired feedback signals.

The pitch and roll actuator position signals are also picked off and applied through interface networks to drive a modified artificial horizon indicator on the control simulator front panel.

Failure detection in the electronic circuits of the Sperry FBW system is accomplished by the utilization of a 5 KH$_z$ tracer signal which appears throughout the channel electronic circuits. Saturation of any element or simple failure of the element will eliminate the tracer signal and cause the internal logic to isolate the faulty channel and transfer the mode of operation of the system to the next lower order of redundancy.

1.3   System Mechanization Description

1.3.1   Sidearm Controller

The sidearm controller shown in Fig. 4 is a three axis, spring centered controller. The output in each axis is proportional to control stick position. In the pitch axis there are four independent synchro transducers which are individually excited from the channel electronics power supplies. The roll and yaw axis each contain one synchro transducer which is excited from the model channel electronics power supply. To simulate the quad-redundant stick in these axes, four roll and yaw output signals are electronically generated from one synchro output.

1.3.2   Channel Electronics

Each axis of the system electronics is comprised of three active channels and a model channel. The electronics utilize thick film replaceable modules packaged in compact ATR racks as shown in Fig. 5. The active channel electronics are interchangeable and keyed to prevent their misuse as a model channel.

Figure 3. Lateral-Directional Axes Block Diagram
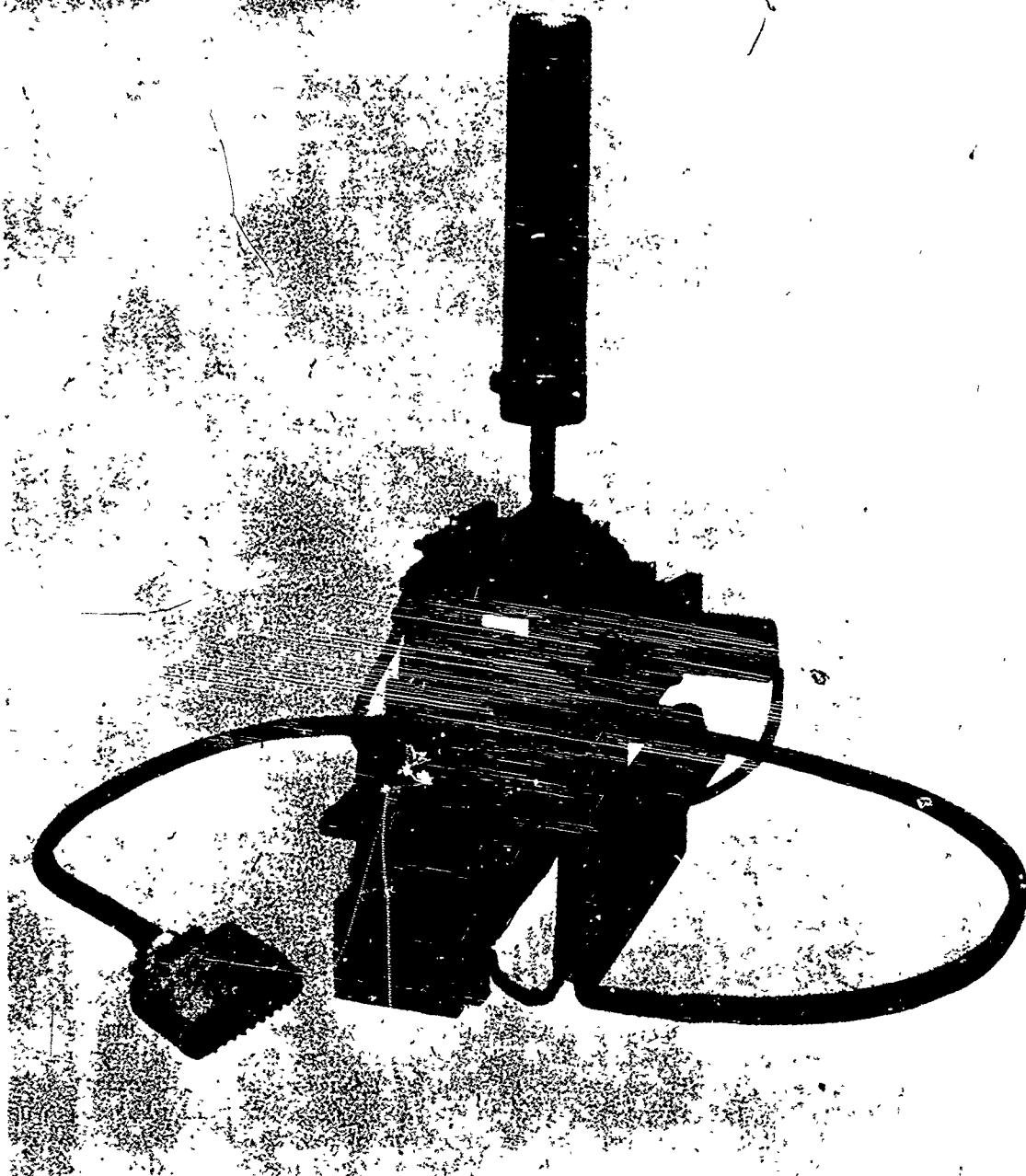
Figure 4. Side Arm Controller

7
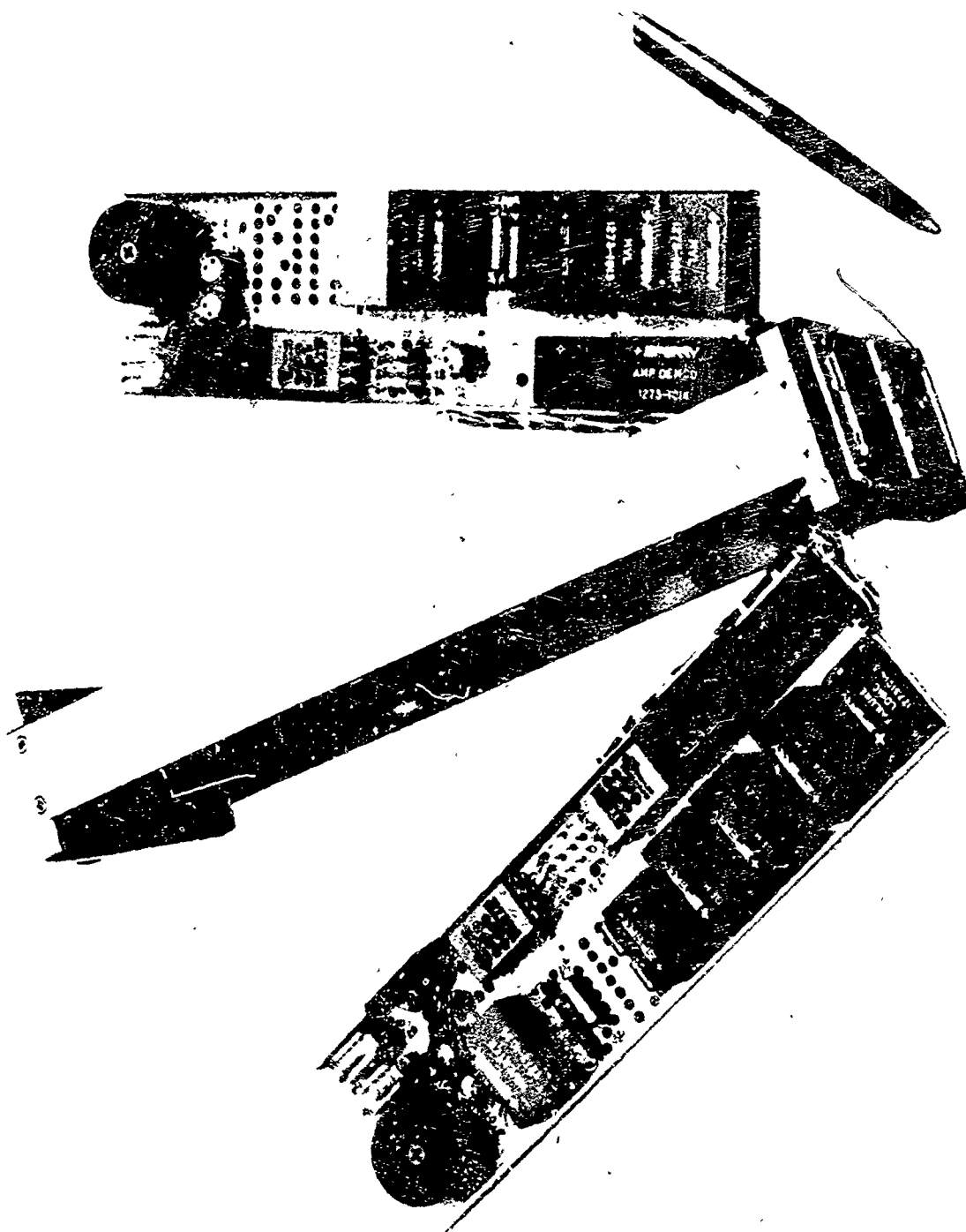
Figure 5. Fly-By-Wire Channel Electronics Chassis

8

The active channels drive active electrohydraulic actuators (models in the roll and yaw axis) while the model channel develops a model of the actuator for monitoring purposes. The channel electronics contain regulated power supplies, tracer signal generators, signal shaping and summation networks, servoactuator drive, monitoring and failure reporting displays.

1.3.3 Control Simulator

The Control Simulator shown in Fig. 6 contains the B-47 analog model, buffers and steering networks to process the channel electronic failure logic signals, failure annunciator and axes status lamp drivers, aircraft displays and all engage switches and channel discretes required for channel engagement. In addition the control simulator contains a clocked logic network to systematically evaluate the status of the channel electronics by determining their response to hardover inputs and a switch matrix for intentionally inserting preselected failures. This clocked logic network provides automatic checkout of the failure detection and removal characteristics of the mechanization prior to engagement. The control simulator also acts as a system junction box for the channel electronics, the actuator, and the sidearm controller.

1.3.4 Triple Redundant Actuator

The triple redundant actuator shown in Fig. 7 consists of three hydraulically independent servoactuators connected in parallel to a common load. Actuator synchronization is accomplished by the force sharing technique.

The channel electronics drive jet pipe servovalves. Each servovalve commands a spring centered second stage valve or servoram. As shown in Fig. 8, each servoram is mechanically engaged to a force summing shaft. This force summing shaft is connected to the main control valves controlling the flow to the output actuator drive areas. Mechanical position feedback was used from the actuator to the main control valve. In addition, an external linkage is connected to the feedback link to provide a mechanical input to the actuator. This link is normally adjusted for the ideal trim conditions and clamped to the actuator body.

9
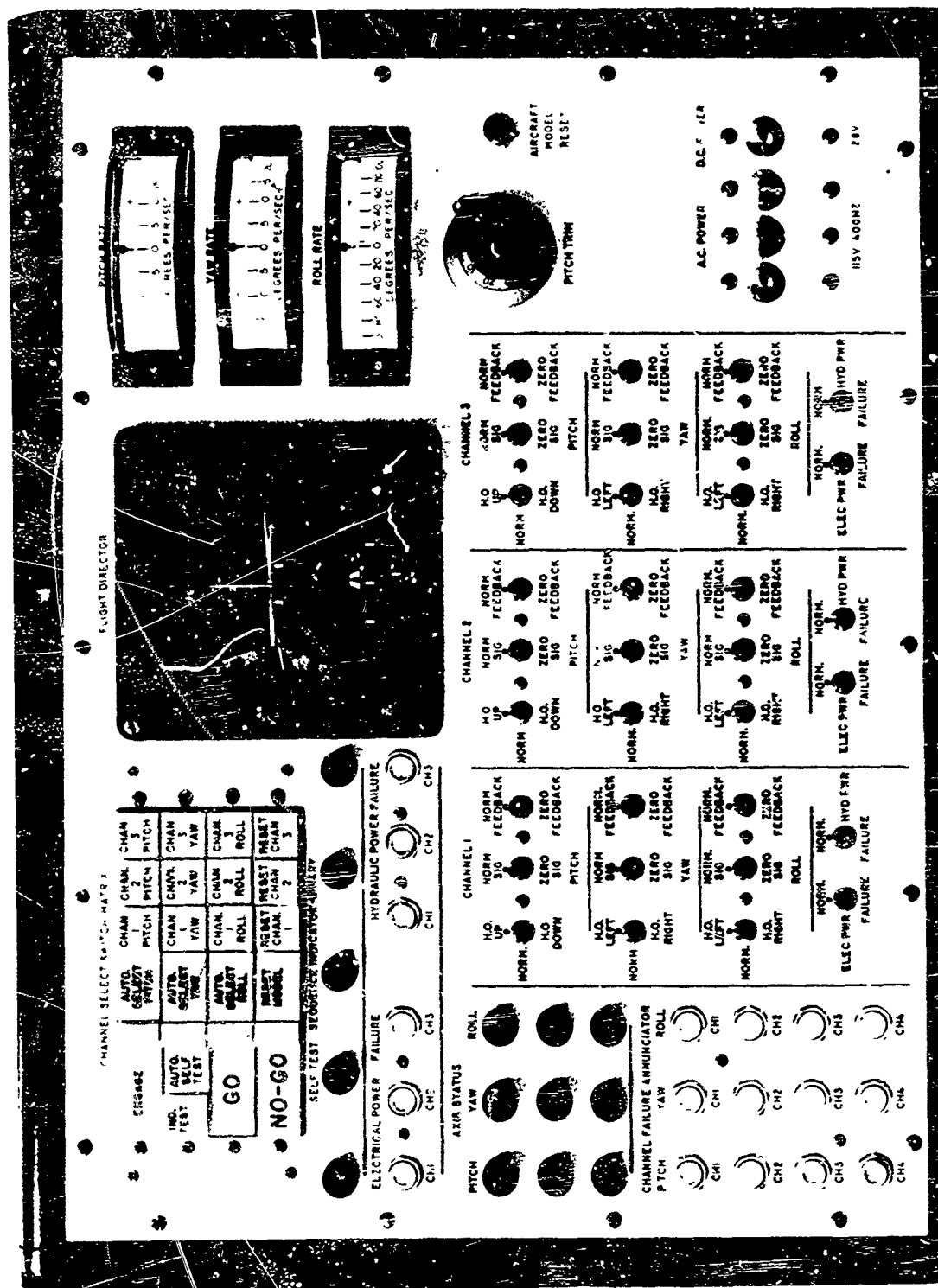
Figure 6. B-47 Control Simulator Front Panel
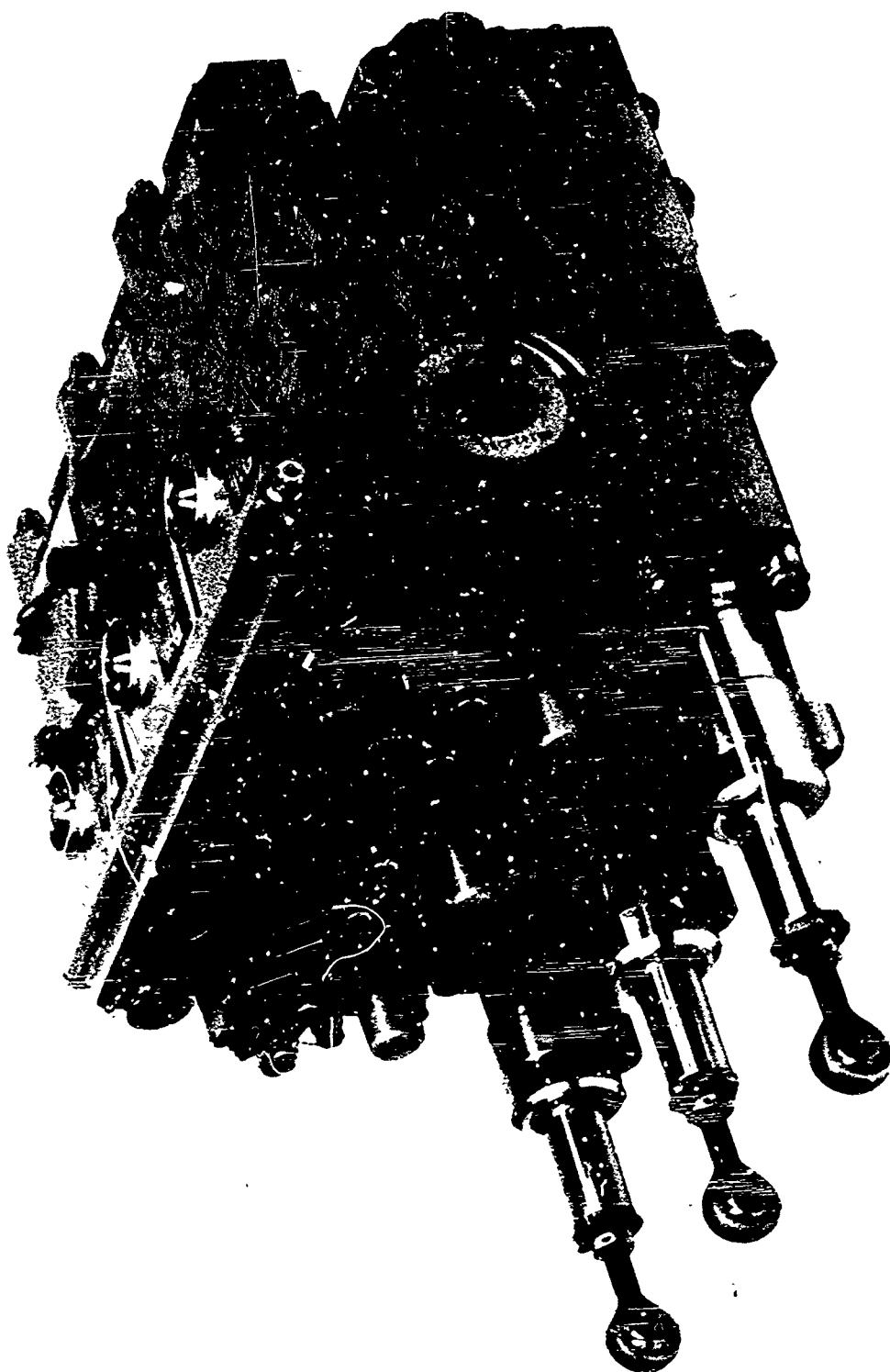
Figure 7. Triple Redundant Actuator

11
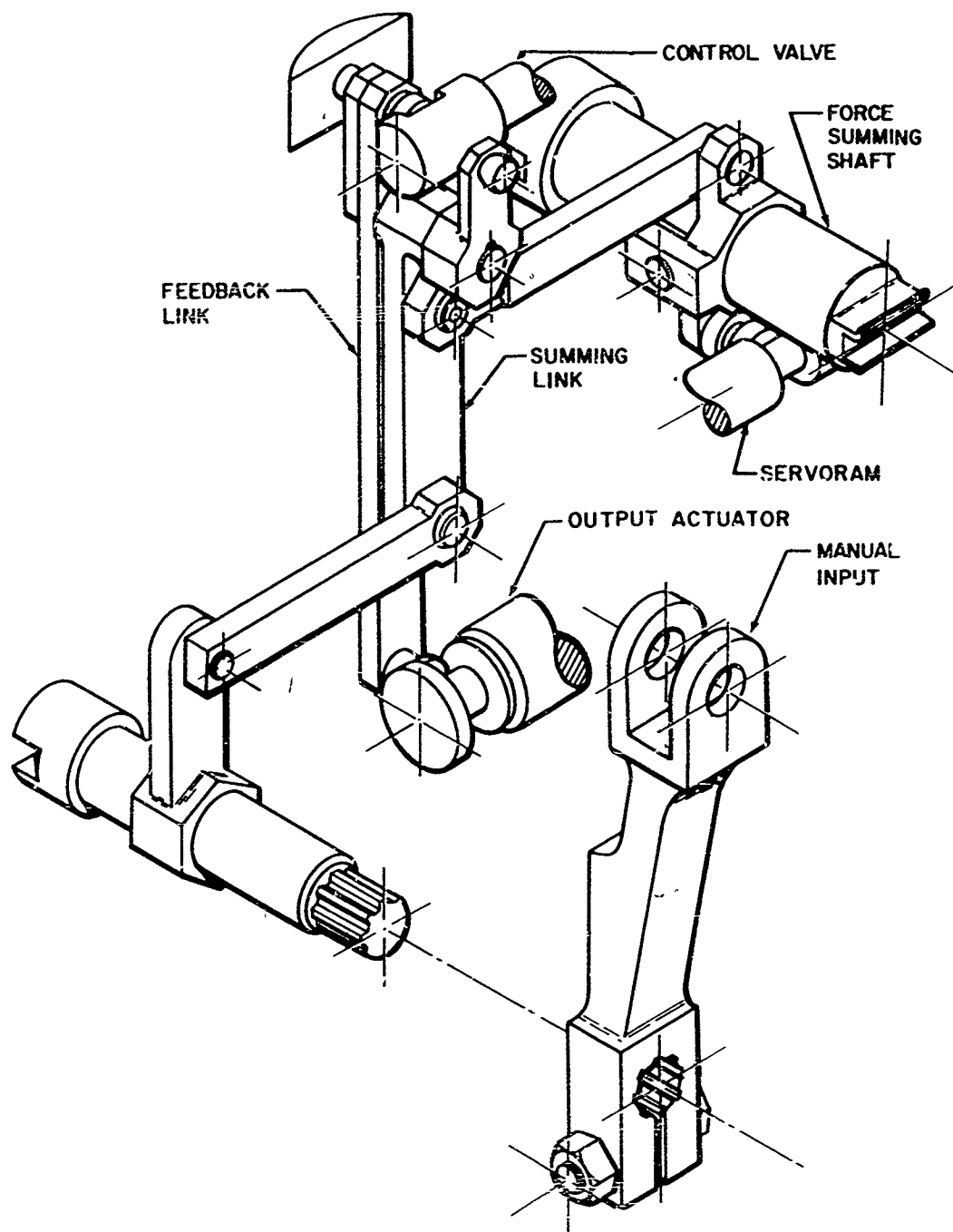
Figure 8.   Internal Linkage Arrangement

Each section of the force summing shaft is aligned relative to the others and the sections mechanically locked together so that any one servoram may drive all three control valves. Because of the use of jet pipe servovalves, the drive areas of inactive servorams are interconnected through the large servovalve flow passages.

Each actuator section is also equipped with a solenoid valve to cut off the servovalve supply pressure. A bypass load limiter is also incorporated in each actuator section to interconnect the section drive areas. The bypass load limiter operates when a static or dynamic mismatch between channels creates a pressure differential that would over-stress the mechanical linkage within the actuator.

The servoram of each actuator is loaded by the force output of the other servorams and a force fight phenomena exists if there is a discrepancy among the three active channels. The Sperry FBW system utilizes pressure equali-zation techniques to reduce interchannel discrepancies and the resulting force fight between servorams to a level of less than 1% for an input mismatch of as much as 10%.

The differential pressure across each servovalve is voted in a midvalue logic network in each channel and an error signal is applied as a feedback at the summing junc-tion of each valve drive servoamplifier to force the indi-vidual channels to approach the midvalue.

1.4 Test Description

The performance of the Sperry FBW system was evaluated by determining the frequency response and phase shift charac-teristic and the control channel failure removal and transfer characteristic in the two fail operate, fail operate and fail safe modes of operation.

The pitch axis of the Sperry FBW system is the only control axis that incorporates an active actuator, and thus was the only axis evaluated in this investigation.

1.4.1 Dynamic Response - Secondary Actuator

The Sperry FBW system was instrumented for frequency response and phase shift measurements as shown in Fig. 9.

13
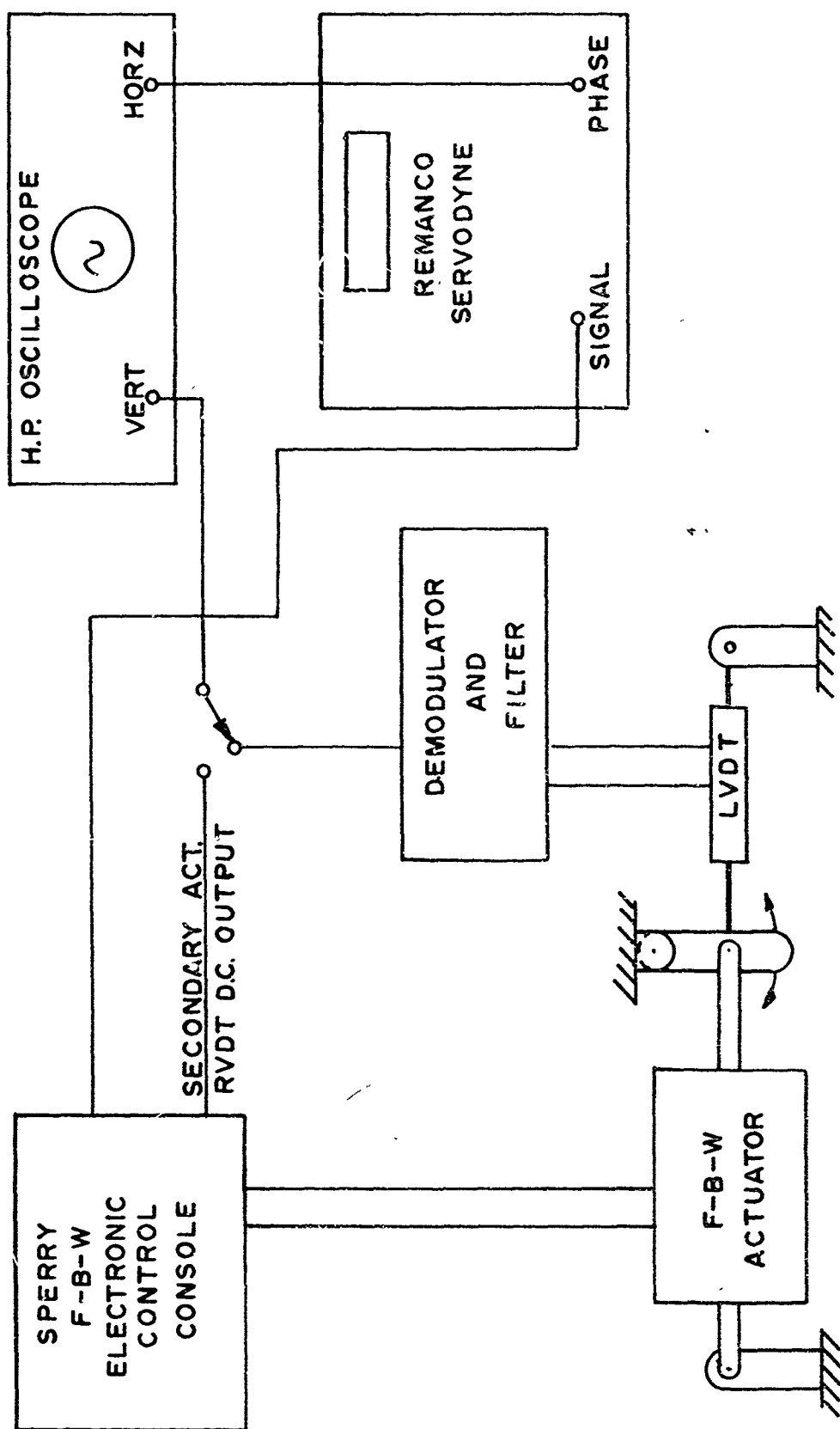
Figure 9. Sperry FBW System Test Stand

To allow evaluation of the Sperry simulation strictly
as a redundant actuator mechanization, (without the modify-
ing effects of the B-47 aircraft normal acceleration and
pitch rate feedback signals) the internal B-47 aircraft
model was disabled by removing a jumper cable provided for
this purpose. The pitch axis internal electronics incor-
porated a forward path element having a proportional and
integral characteristic (ref. Fig. 2). Since the integral
characteristics of the element did not affect the dynamic
operation of the pitch axis, the forward path element was
not eliminated for the tests performed on the pitch axis.

The demodulated output from the sidearm controller
was disconnected from the summing junction of the initial for-
ward loop operational amplifier. The input signal from the
function generator was connected to the summing junction of
each active channel through the input resistor normally con-
nected to the sidearm controller demodulated output signal.

The Sperry FBW system was energized in the two fail
operate mode and the trim input control was adjusted until the
servoram RVDT output approached zero. The pilot input mech-
anical linkage position was adjusted to provide a main ram
extension of 1.275 inches from the fully retracted position.

To allow frequency response measurements, the demodu-
lated and filtered output from the servoram RVDT was applied
to the horizontal axes of a DC coupled scope. The response
measurements were made at a main ram deflection of $\pm$ .050
inches. Particular failure modes were obtained by inter-
rupting the power source of selected channels.

1.4.2 Dynamic Response - Main Ram

The motion of the main ram of the servoactuator was
obtained from an LVDT mechanically connected to the hinged
flap that supports the rod end of the main ram. The LVDT
was connected to the hinged flap at a point opposite to
the attachment of the main rams of the servoactuator but
on the same horizontal thrust plane.

The LVDT was excited from a 28 volt, 400 H_z source.
The output from the LVDT was synchronously demodulated and
filtered with a second order lag network having a 3 db break
point at 80 H_z or approximately one order of magnitude above
the expected response of the Sperry Fly-By-Wire system.

15

The dynamic response of the main ram was determined with the same procedure developed for the secondary actuator or servoram.

1.4.3 Control Channel Failure Removal and Transfer Characteristics

The purpose of this investigation was to evaluate the control channel failure removal and transfer characteristics of the Sperry FBW system.

Channel failures were simulated by applying hardover inputs or by the removal of hydraulic or electric power. Signal injection and power removal functions were accomplished by utilizing the failure injection switch matrix provided on the panel of the Sperry control simulator.

The effect of the simulated channel failures was evaluated by observing the transient and long term deviations of the servoactuator main ram when the failures were injected.

The control channel failure removal and transfer characteristics were determined by injecting a specific failure into the pitch axis of the control channel electronics to cause the Sperry FBW system logic to sequentially transfer control from the two fail operate mode to the fail safe mode.

After the injection of each failure and the stabilization of the event resulting from the simulated failure, the main ram zero pitch trim position was re-established prior to initiation of the next failure simulation.

The servoactuator main ram position was monitored with the LVDT instrumentation and the demodulated and filtered LVDT output was connected to the vertical terminals of a DC coupled oscilloscope. The transient effect of failure injection was recorded with a Polaroid Camera attachment mounted to the oscilloscope.

1.5 Test Results and Analysis

In the process of preparing the Sperry FBW system for evaluation, an excessive voltage was accidentally applied to the 400 H_z AC power input of the Sperry control channel

16

electronics. The channel electronics were not protected
and the channel electronic power supplies and some logic
modules were damaged. Sperry personnel repaired the
channel electronic modules and rewired the 400 cycle,
3 phase input to allow the system to be operated from
a single phase, 400 cycle source. Sperry personnel also
stated that the FBW system appeared to be operating cor-
rectly.

The pitch axis electronics contained a forward path
element having a proportional and integral characteristic.
With the aircraft model disabled, feedback around the in-
tegral characteristic of the element was eliminated, al-
lowing the element to generate the drift observed during
the evaluation testing. Since the evaluation tests were
of a dynamic nature and the integral characteristic con-
tributes only to DC drift characteristic, no attempt was
made to remove the subject elements characteristic from
the forward path. Fig. 10 shows the measured frequency
response of the element over the performance range used
to evaluate the actuator channels. As can be seen from
the plot, the integral characteristic of the element did
not affect the frequency response measurements in any way.
The principle effect of the element was the gradual DC
drift instability observed during the evaluation testing
and appearing in the failure removal characteristic photo-
graphs.

As anticipated, with the B-47 model disconnected, the
forward path free integrator characteristic required DC
trim corrections during measurement of the dynamic res-
ponse characteristic. The zero trim position of the force
summing shaft could be maintained if prior to each dynamic
test, the input was short circuited and the pitch trim
very carefully adjusted until all drift was eliminated.

In different modes of operation, it was necessary to
vary the drive signal to maintain a constant 1 H_z output
deflection at the force summing shaft.

1.5.1 Dynamic Response - Secondary Actuator

The frequency response and phase shift characteristics
of the secondary actuator or servoram are shown in Fig. 11
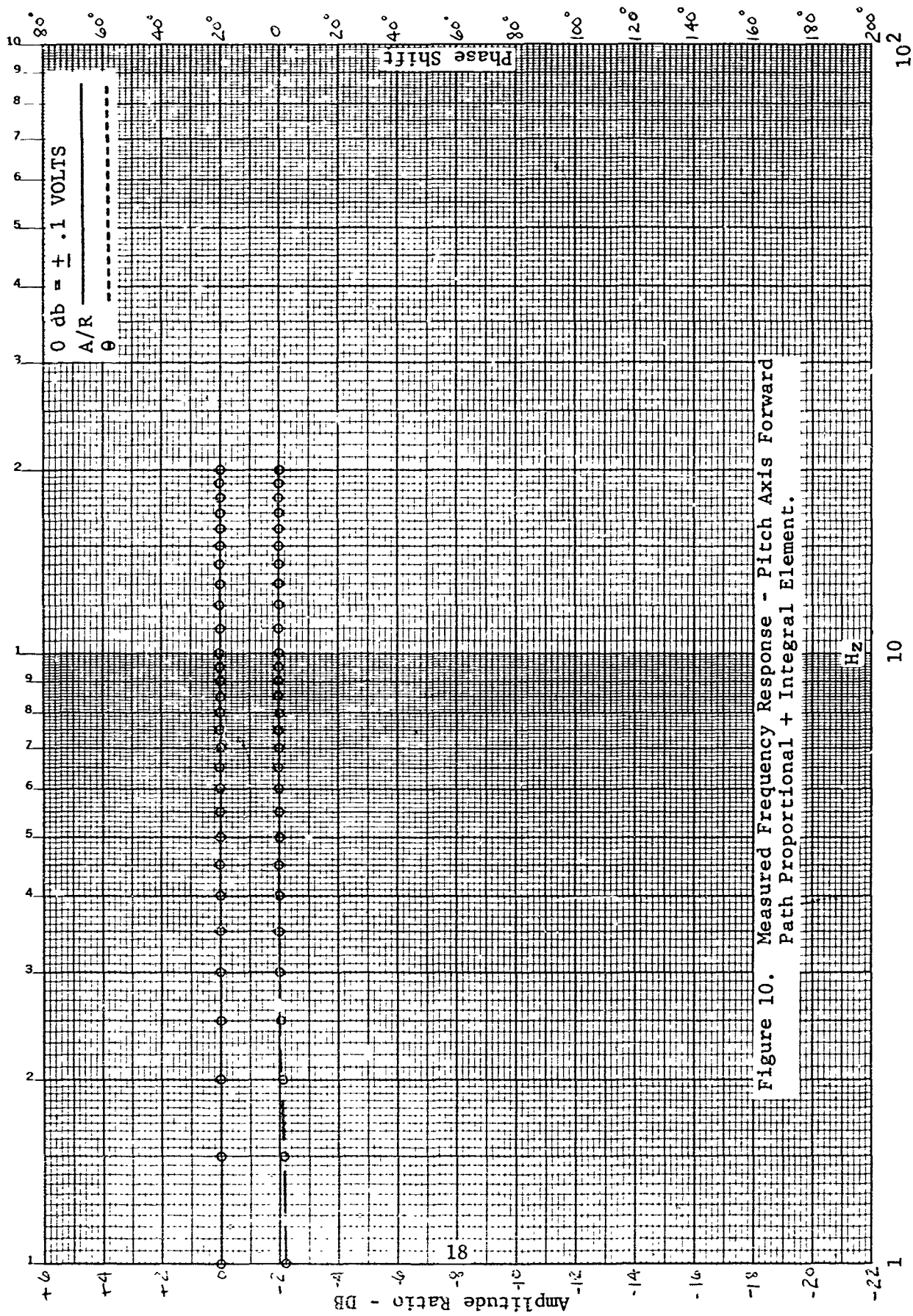
Figure 10. Measured Frequency Response - Pitch Axis Forward
Path Proportional + Integral Element.

through 18. The frequency response and phase shift charac-
teristics in the two fail operate mode, Fig. 11 and the fail
operate mode, Fig. 12 through 14, are typical of a well
damped second order system with some higher order network
effects present. The damped natural frequency in these
modes varied from 6.0 H_Z to 8.5 H_Z with the damping ratio
(second order equivalent) varying from .3 to .7.

The amplitude and phase shift characteristics in the
fail safe and select modes of operation exhibited degraded
response from the two fail operate and fail operate modes
of operation. The degraded response reflected the reduced
driving force to drive the servoram with just one channel
operating. The decreased effective force in the fail safe
and select modes results in a decreased dynamic response,
which is typical of a force summed unit under constant
loading.

When channel two was operated independently, the trim
characteristic of the particular forward path integrator
plus the other channel two components gave a null charac-
teristic that prevented dynamic response measurements.

Fig. 15 and 16 show the measured response of channel
1 and 3 operating in the fail safe mode, with the electronic
model operating. The channel 3 response showed no peak-
ing and a smooth roll off of response above 5 H_Z. The
-3db point occurred at 8 H_Z. The channel 1 response did
not particularly resemble the channel 3 characteristics.
The amplitude response started to attenuate gradually
above 1.5 H_Z, but maintained a response which was only
-3db down at 9.5 H_Z.

Fig. 17 and 18 show the response in the channel se-
lect mode for channel 1 and channel 3. The measured res-
ponse differed slightly from the fail safe mode of opera-
tion with the same respective channels. Channel 1 exhi-
bited a smooth roll off, no peaking and a response which
was -3db at 6.5 H_Z. This was a slightly lower response
than the fail safe mode, but with what appeared to be a
response more typical of a linear servo system. Channel
3's operation in the select mode showed some irregularity
above 10 H_Z, but exhibited a relatively smooth response
having a -3db point at 6.5 H_Z.

19
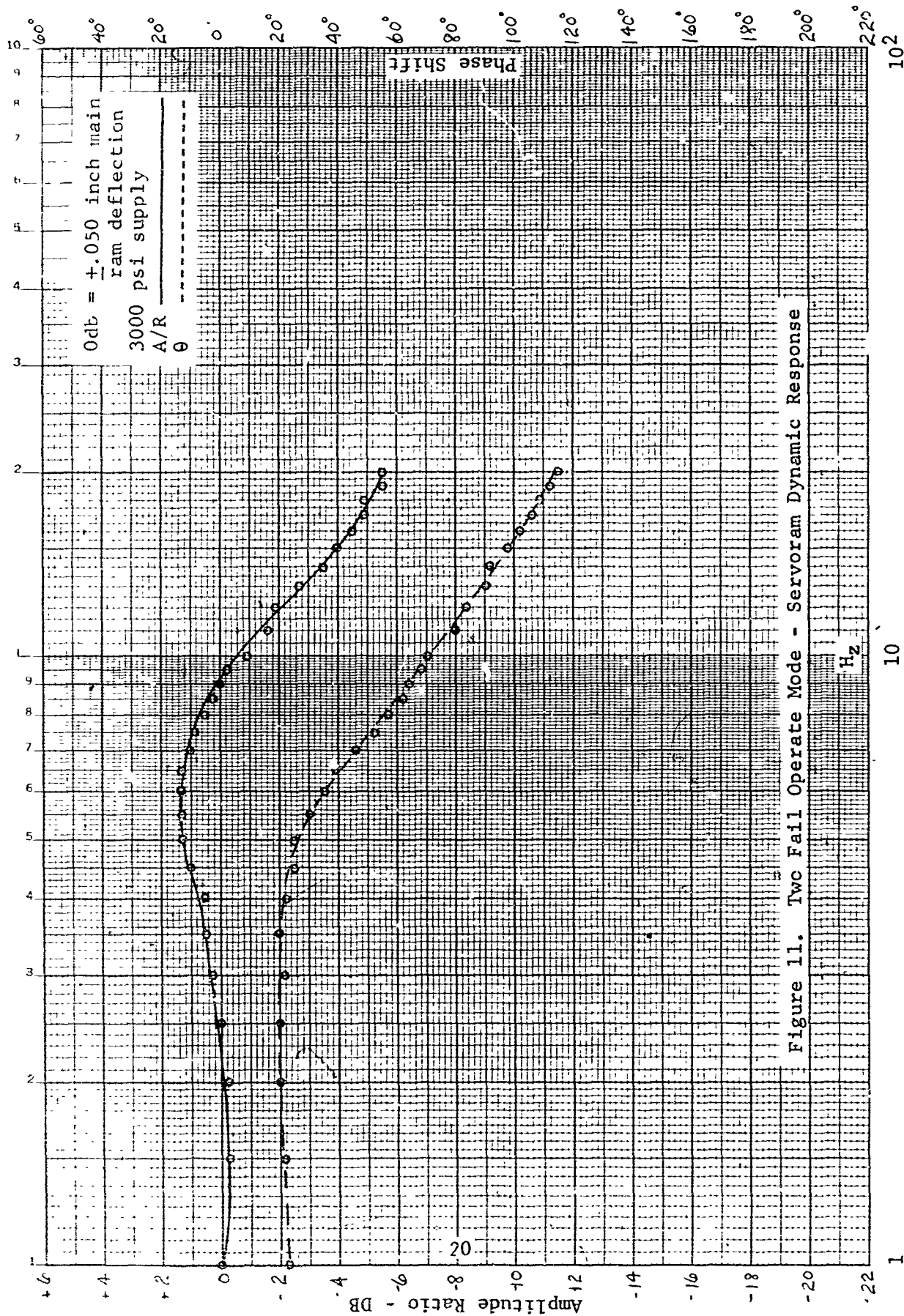
Figure 11. Two Fail Operate Mode – Servoram Dynamic Response

Odb = ±.050 inch main
ram deflection
3000 psi supply
A/R ————
θ - - - -

Phase Shift

Amplitude Ratio - DB

Hz

Figure 12. Single Fail Operate Mode - Servoram Dynamic Response Channel Two and Three Operating

21

Figure 13. Single Fail Operate Mode - Servoram Dynamic Response Channel One and Three Operating

Figure 14. Single Fail Operate Mode - Servoram Dynamic Response Channel One and Two Operating

0db = ±.050 inch main ram deflection
3000 psi supply
A/R ———
θ ———

Phase Shift

Amplitude Ratio - DB

Hz

Figure 15. Fail Safe Mode - Servoram Dynamic Response
Channel Three Operating

0db = ±.050 inch main
ram deflection
3000 psi supply

A/R ————
θ — — — —

Amplitude Ratio - DB

Phase Shift

Hz

24

Figure 16. Fail Safe Mode - Servoram Dynamic
Response Channel One Operating

Phase Shift

$\cap$db = $\pm$.050 inch main
ram deflection

3000 psi supply

A/R ————
θ - - - - - -

Phase Shift

60° 40° 20° 0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220°

Amplitude Ratio ~ DB

+6 +4 +2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22

Hz

1   10   10²

26

Figure 17. Channel One Select Mode - Servoram Dynamic Response

Figure 18. Channel Three Select Mode - Servoram Dynamic Response

27

1.5.2 Dynamic Response - Main Ram

The frequency response and phase shift characteristics of the main ram are shown in Fig. 19 through 28.

The dynamic response characteristic of the secondary actuator or servoram, (decreased response with decreased effective force) is reflected in the dynamic response of the main ram in the various modes of operation.

The two fail operate frequency response (-3db point) was 6.0 H_z. The variation of the frequency response between the different channel combinations for the fail operate mode was from 5 H_z to 8 H_z (for the -3db point).

The degradation of the main ram dynamic response in the fail safe mode of operation, Fig. 23 through 25, correlates with the observed downward trend in the dynamic response of the servoram in the same redundant mode. The frequency response measurements in the fail safe mode (with the exception of channel 1 operation) gave a -3 db point which varied from between 4.75 to 7 H_z with the different channels operating. The channel 1 -3db point of 2.75 H_z is different than with the other channels operating.

The main ram dynamic response in the select modes of operation, Fig. 26 through 28, is degraded in reference to the servoram response in the same redundant mode of operation. The response variation between channels is small, with the -3db point ranging from 2 to 2.5 H_z.

The decreased dynamic response in the fail safe and select modes of operation is related to the decreased effective driving force available for driving the servoram when operating in these modes.

1.5.3 Failure Removal Characteristic

This investigation was limited to an evaluation of the transient effect of the insertion of positive and negative hardover signals into the control channel electronics. The limited scope of this effort did not permit an evaluation of the effects of open input or open feedback failures, but these effects are generally less severe, in terms of

Figure 19. Two Fail Operate - Main Ram Dynamic Response

Legend in plot:
0db = ±.050 inch main
ram deflection
3000 psi supply
A/R ————
θ — — — —

Axis labels:
Phase Shift
Amplitude Ratio - DB
Hz

29

Odb = ±.050 inch main
ram deflection
3000 psi supply
——————— A/R
- - - - - - - θ

Phase Shift

Amplitude Ratio - DB

Hz

Figure 20.   Single Fail Operate - Main Ram Dynamic Response
Channel One and Two Operating
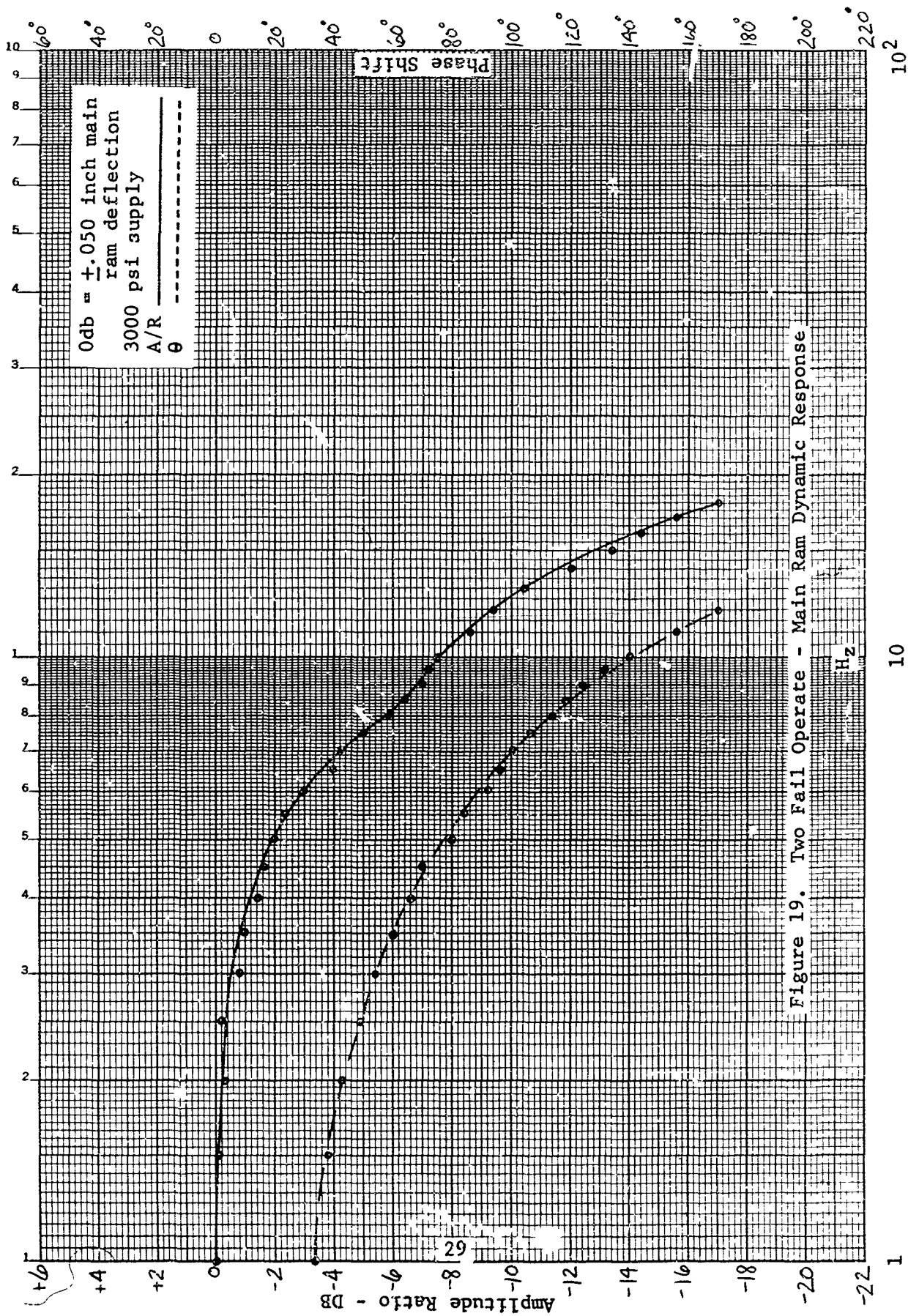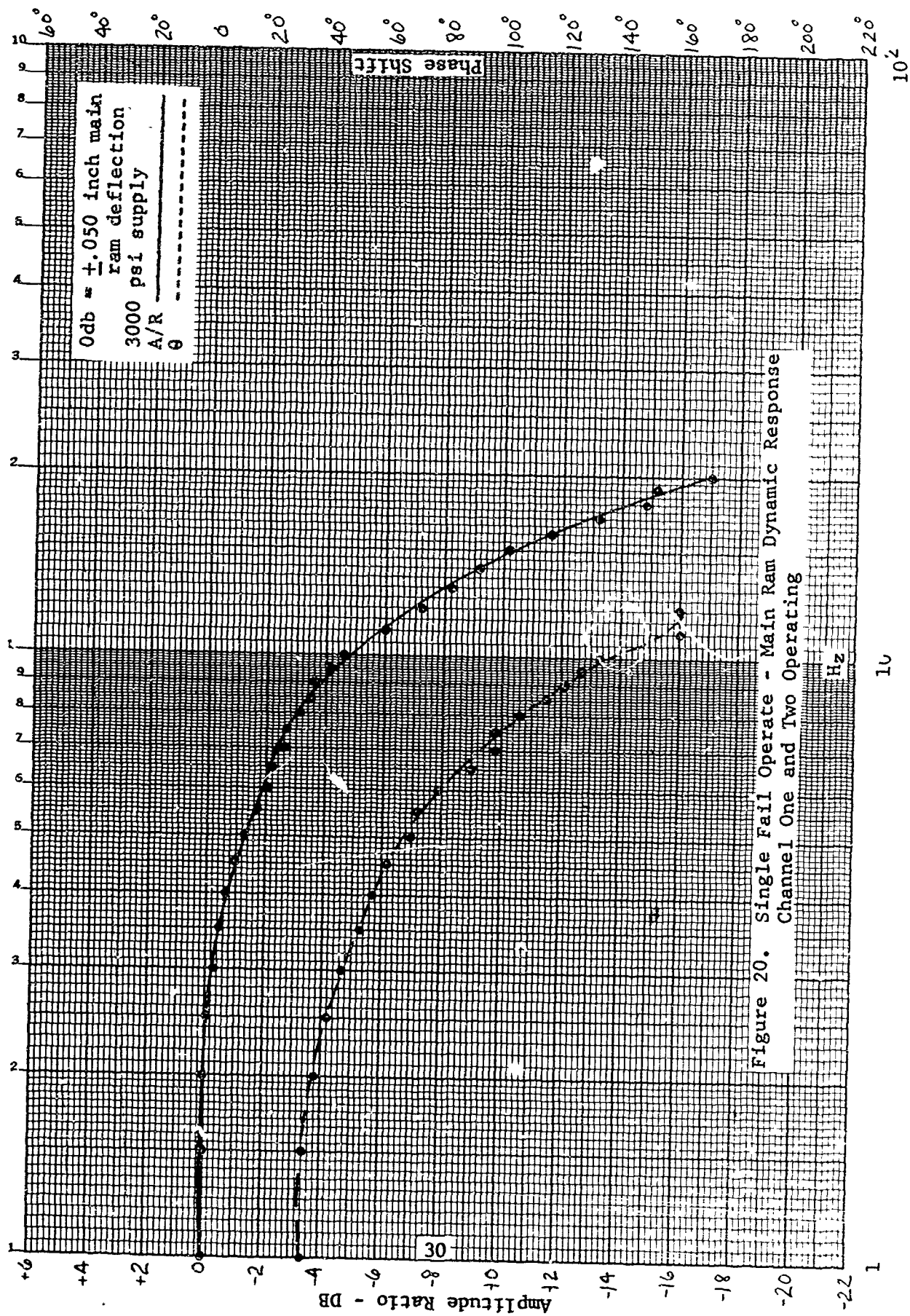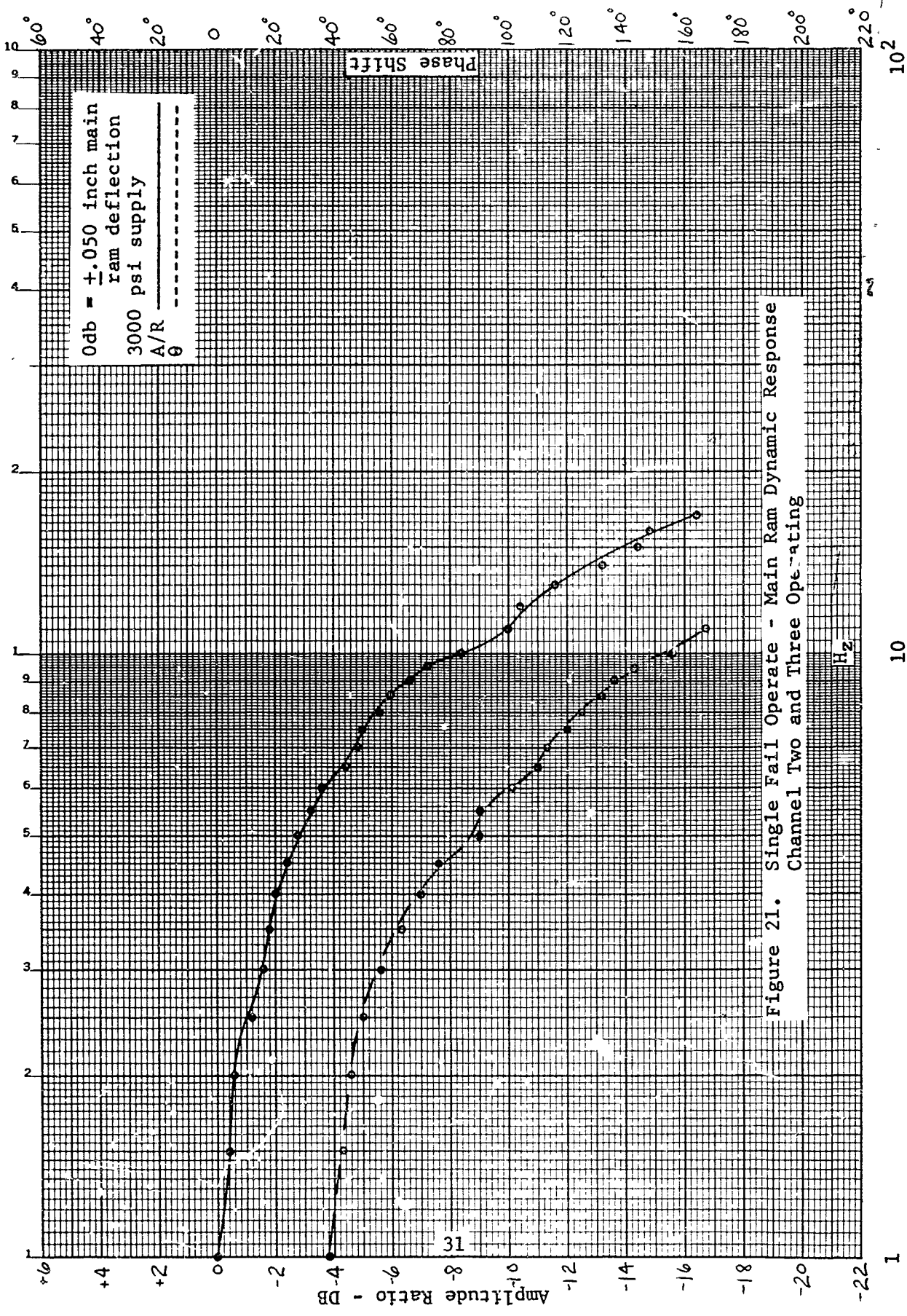
Figure 21. Single Fail Operate - Main Ram Dynamic Response
Channel Two and Three Operating

31

Figure 22. Single Fail Operate – Main Ram Dynamic Response
Channel One and Three Operating

Figure 23. Fail Safe Mode – Main Ram Dynamic Response
Channel One Operating

0db = ±.050 inch main
ram deflection
3000 psi supply

A/R
θ

Phase Shift

Amplitude Ratio - DB

Hz

Figure 24. Fail Safe Mode - Main Ram Dynamic Response
Channel Two Operating

Figure 25. Fail Safe Mode – Main Ram Dynamic Response Channel Three Operating

Odb = ±.050 inch main ram deflection

3000 psi supply

A/R ―――――
θ ------

Phase Shift

Amplitude Ratio - DB

Hz

35

Figure 26. Channel One Select Mode — Main Ram Dynamic Response

36

Figure 27. Channel Two Select Mode – Main Ram Dynamic Response

Odb = +.050 inch main
ram deflection

3000 psi supply

A/R ....
θ -----

Phase Shift

Amplitude Ratio - DB

Hz

37

Phase Shift

60°
40°
20°
0°
20°
40°
60°
80°
100°
120°
140°
160°
180°
200°
220°

0db = ±.050 inch main
ram deflection
3000 psi supply

A/R
θ

Amplitude Ratio - DB

+6
+4
+2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22

38

Hz

10

10²

Figure 28. Channel Three Select Mode - Main Ram Dynamic Response

the aircraft pitch rate response, than hardover signals.
Furthermore, the effect of the insertion of hardover signals
was evaluated in terms of the positional deviation of the
main ram, rather than the pitch rate of the airframe.

1.5.3.1 Two-Fail Operate Mode

The Sperry FBW system consistently decoupled the chan-
nel into which the hardover signal was applied within 200 to
400 milliseconds after the initiation of the simulated fail-
ure. The main ram transient deflection that resulted from
the hardover input was .072 to .110 inches or less than
1.3° equivalent elevator pitch change, as shown in Fig.
29 through 34.

The position drift (after failure removal) shown in
Fig. 29 through 34 is caused by the free integrator in
the forward path element of the pitch axis mechanization.
The drift would not have existed with the B-47 aircraft
model inserted in the control loop.

1.5.3.2 Fail Operate Mode

The Sperry FBW system consistently decoupled the chan-
nel into which the hardover signal was applied within 250
to 350 milliseconds after the initiation of the simulated
failure. The main ram deflection resulting from the hard-
over input was .100 to .200 inches or less than 2.4° equi-
valent elevator change, as shown in Fig. 35 through 38.

1.5.3.3 Fail Safe Mode

The Sperry FBW system consistently decoupled the chan-
nel into which the hardover signal was applied within 250
to 500 milliseconds after the initiation of the simulated
failure. The main ram deflection that resulted from the
hardover input was .300 to .630 inches or less than 7.5°
equivalent elevator pitch change, as shown in Fig. 39 and
40.

The main ram retained an offset in the direction of
the hardover signal of 0.320 inches for hardover positive
and 0.216 inches for hardover negative.

The offset conditions experienced in this mode of
operation may be caused by the high main ram seal fric-
tion force.
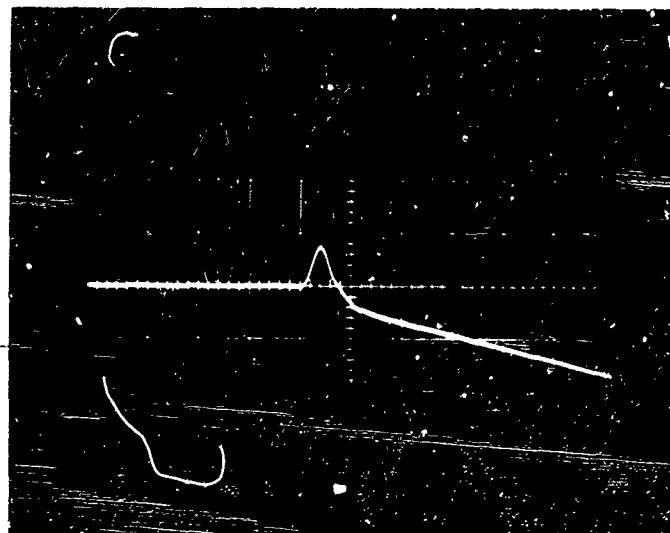
Two Fail Operate Mode
Channel One - Hardover Positive
Vertical - .090"Main Ram Def/Major Division
Horizontal - 0.5 Sec/Major Division
Input - None
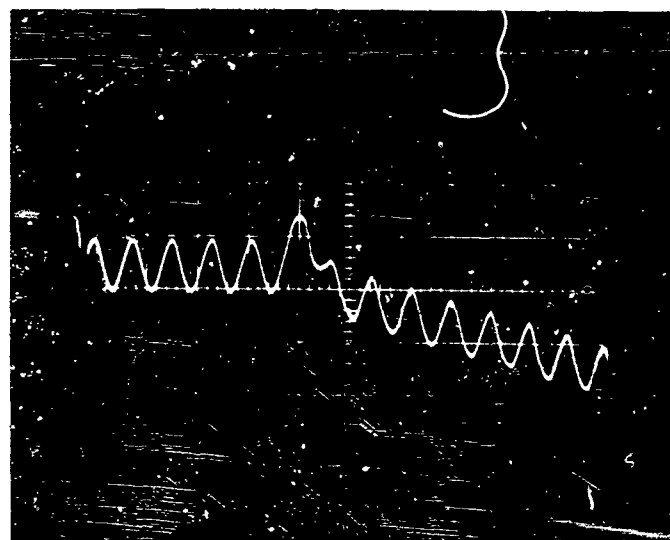
Two Fail Operate Mode
Channel One - Hardover Positive
Vertical - .090"Main Ram Def/Major Division
Horizontal - 0.5 Sec/Major Division
Input - 3H$_z$

Figure 29. Channel One Failure Removal Characteristic
Two Fail Operate Mode - Positive Input

40

Two Fail Operate Mode
Channel One - Hardover Negative
Vertical - .090″ Main Ram Def/Major Division
Horizontal - 0.5 Sec/Major Division
Input - None

Two Fail Operate Mode
Channel One - Hardover Negative
Vertical - .090″ Main Ram Def/Major Division
Horizontal - 0.5 Sec/Major Division
Input - $3H_z$

Figure 30.   Channel One Failure Removal Characteristic
             Two Fail Operate Mode - Negative Input
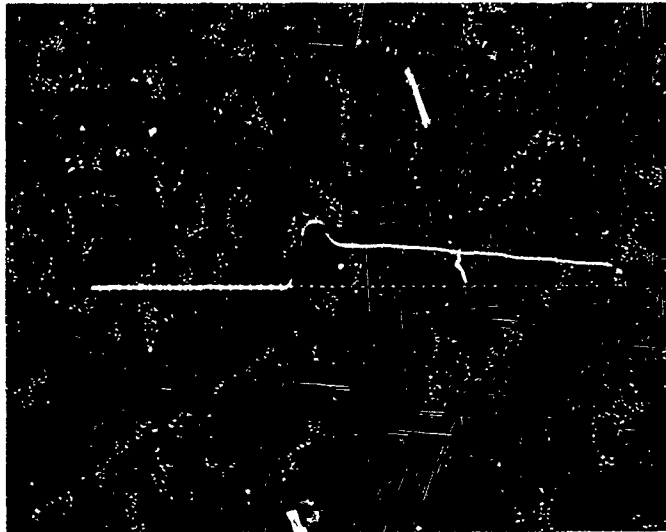
41

Two Fail Operate Mode
Channel Two - Hardover Positive
Vertical - .090″ Main Ram Def/Major Division
Horizontal - 0.5 Sec/Major Division
Input - None

Two Fail Operate Mode
Channel Two - Hardover Positive
Vertical - .090″ Main Ram Def/Major Division
Horizontal - 0.5 Sec/Major Division
Input - $3H_z$

Figure 31.　Channel Two Failure Removal Characteristic
Two Fail Operate Mode - Positive Input

Two Fail Operate Mode
Channel Two - Hardover Negative
Vertical - .090″ Main Ram Def/Major Division
Horizontal - 0.5 Sec/Major Division
Input - None
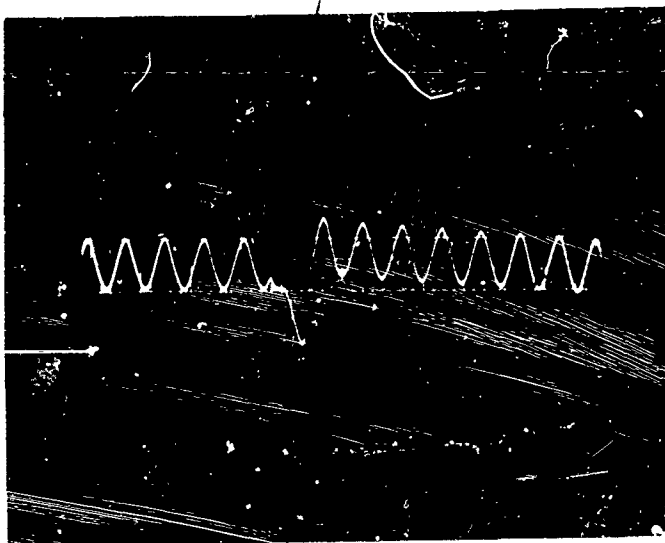
Two Fail Operate Mode
Channel Two - Hardover Negative
Vertical - .090″ Main Ram Def/Major Division
Horizontal - 0.5 Sec/Major Division
Input - $3H_z$

Figure 32. Channel Two Failure Removal Characteristic
Two Fail Operate Mode - Negative Input
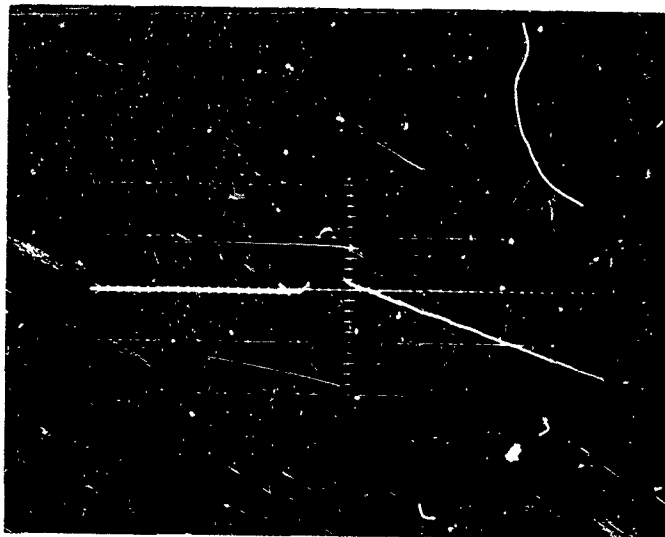
43

Two Fail Operate Mode
Channel Three - Hardover Positive
Vertical - .090" Main Ram Def/Major Division
Horizontal - 0.5 Sec/Major Division
Input - None
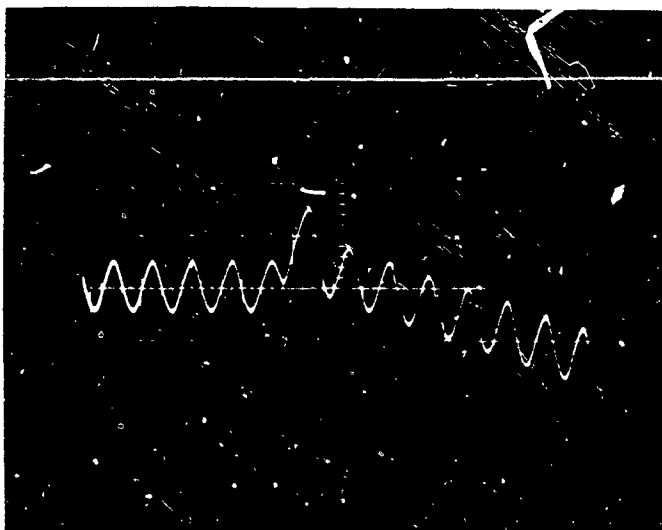
Two Fail Operate Mode
Channel Three - Hardover Positive
Vertical - .090" Main Ram Def/Major Division
Horizontal - 0.5 Sec/Major Division
Input - $3H_z$

Figure 33.   Channel Three Failure Removal Characteristic
             Two Fail Operate Mode - Positive Input

44

Two Fail Operate Mode
Channel Three - Hardover Negative
Vertical - .090 Main Ram Def/Major Division
Horizontal - 0.5 Sec/Major Division
Input - None

Two Fail Operate Mode
Channel Three - Hardover Negative
Vertical - .090 Main Ram Def/Major Division
Horizontal - 0.5 Sec/Major Division
Input - $3H_z$

Figure 34.   Channel Three Failure Removal Characteristic
Two Fail Operate Mode - Negative Input
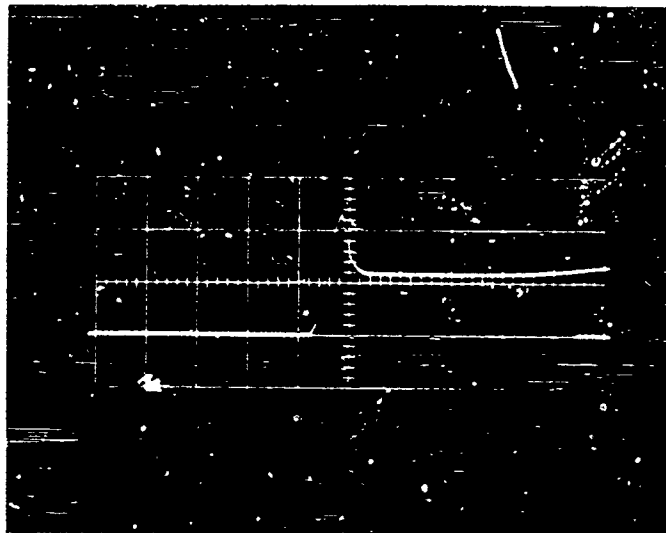
Fail Operate Mode
Channel One - Failed Electrically
Channel Two - Failed Hardover Positive
Vertical - .090″ Main Ram Def/Major Division
Horizontal - 0.5 Sec/Major Division
Input - None
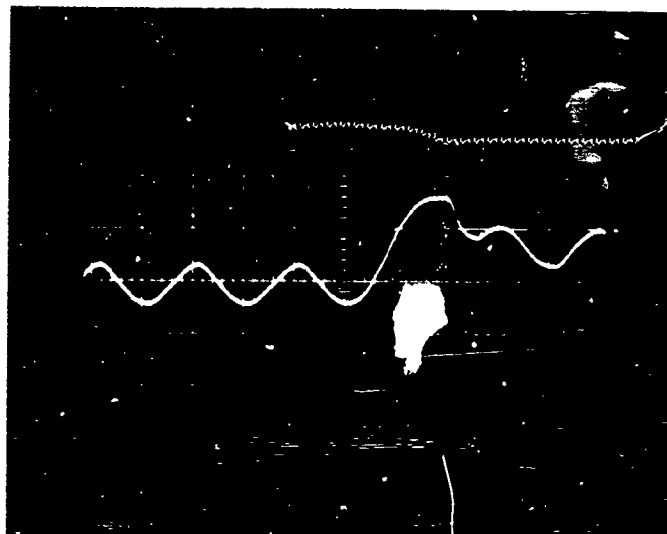
Fail Operate Mode
Channel One - Failed Electrically
Channel Two - Failed Hardover Positive
Vertical - .080″ Main Ram Def/Major Division
Horizontal - 0.2 Sec/Major Division
Input - 3 Hz

Figure 35.   Channel Two Failure Removal Characteristic
            Fail Operate Mode - Positive Input
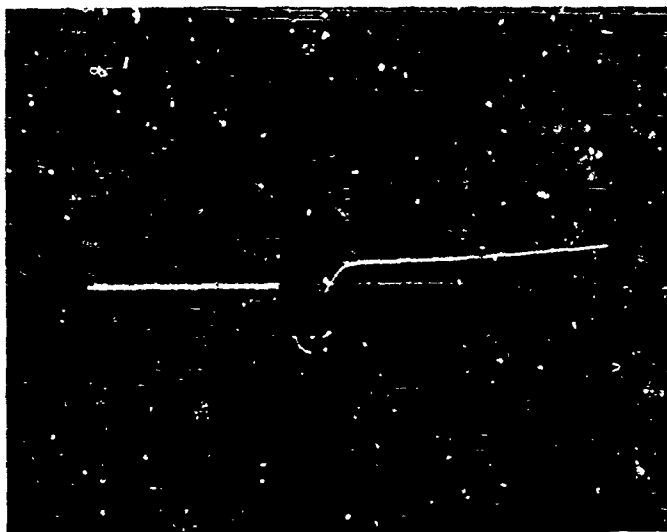
46

Fail Operate Mode
Channel One - Failed Electrically
Channel Two - Failed Hardover Negative
Vertical - .090" Main Ram Def/Major Division
Horizontal - 0.5 Sec/Major Division
Input - None
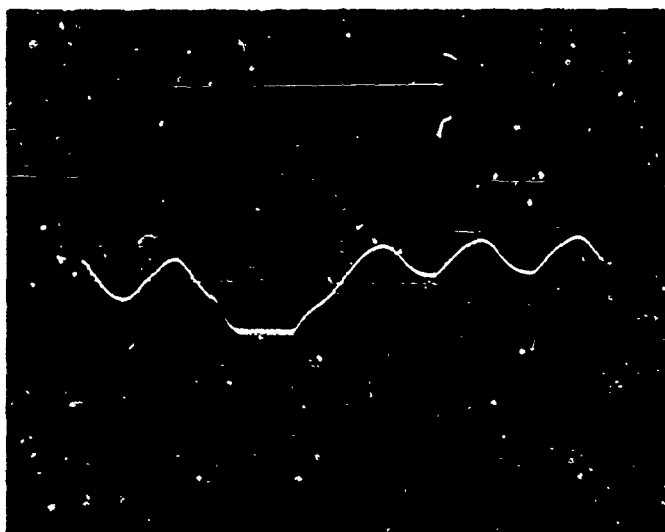
Fail Operate Mode
Channel One - Failed Electrically
Channel Two - Failed Hardover Negative
Vertical - .080" Main Ram Def/Major Division
Horizontal - 0.2 Sec/Major Division
Input - 3 H_z

Figure 36. Channel Two Failure Removal Characteristic
Fail Operate Mode - Negative Input
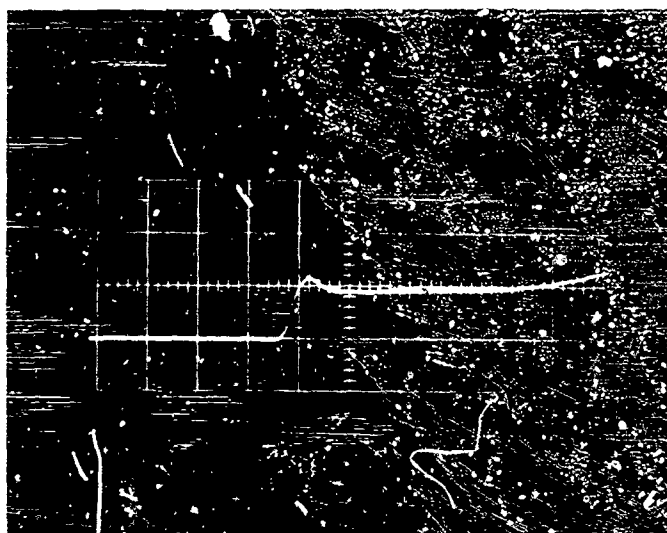
47

Fail Operate Mode
Channel One - Failed Electrically
Channel Three - Failed Hardover Positive
Vertical - .090″ Main Ram Def/Major Division
Horizontal - 0.5 Sec/Major Division
Input - None

Fail Operate Mode
Channel One - Failed Electrically
Channel Three - Failed Hardover Positive
Vertical - .080″ Main Ram Def/Major Division
Horizontal - 0.2 Sec/Major Division
Input - 3 H_z

Figure 37. Channel Three Failure Removal Characteristic
Fail Operate Mode - Positive Input

48

Fail Operate Mode
Channel One - Failed Electrically
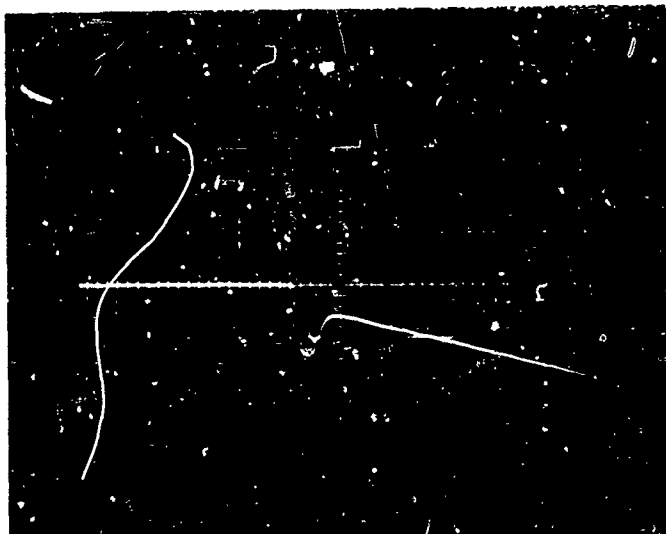Channel Three - Failed Hardover Negative
Vertical - .090" Main Ram Def/Major Division
Horizontal - 0.5 Sec/Major Division
Input - None

Fail Operate Mode
Channel One - Failed Electrically
Channel Three - Failed Hardover Negative
Vertical - .080" Main Ram Def/Major Division
Horizontal - 0.2 Sec/Major Division
Input - 3 H_z

Figure 38. Channel Three Failure Removal Characteristic
Fail Operate Mode - Negative Input
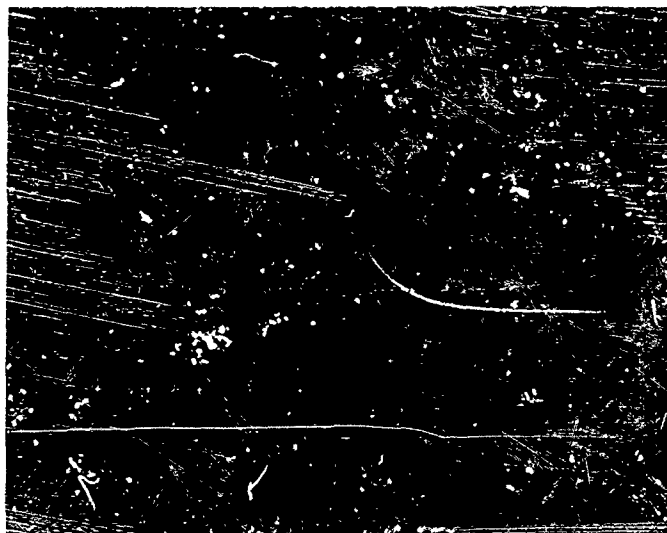
Fail Safe Mode
Channels One & Two - Failed Electrically
Channel Three - Failed Hardover Positive
Vertical - .180 Main Ram Def/Major Division
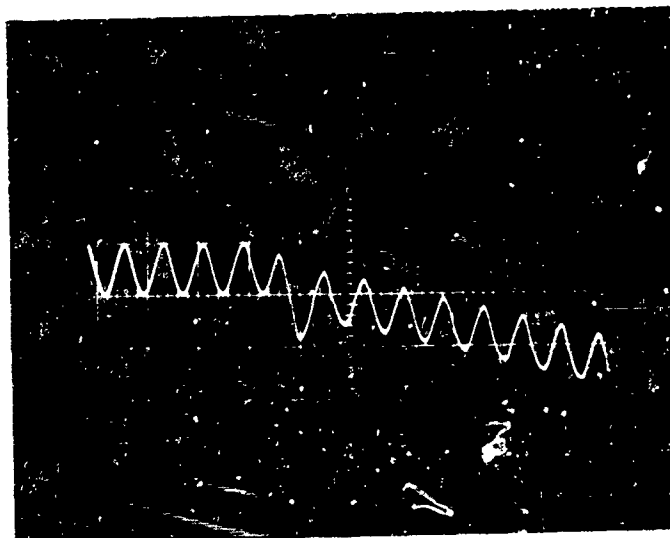Horizontal - 0.5 Sec/Major Division
Input - None
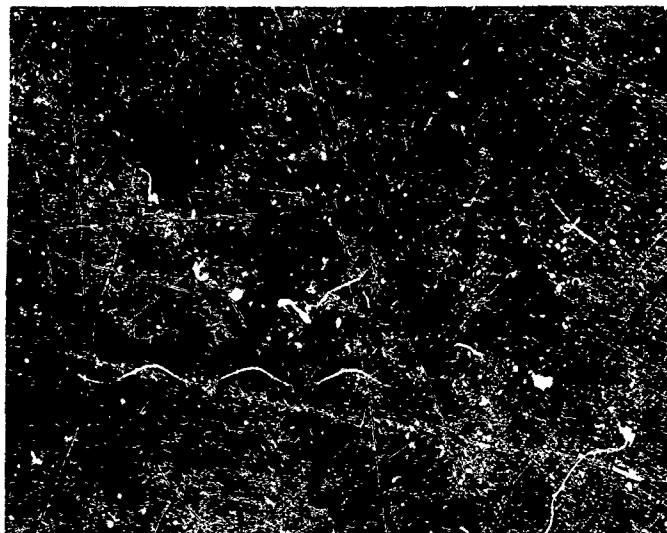
Γ il Safe Mode
Channels One & Two - Failed Electrically
Channel Three - Failed Hardover Positive
Vertical - .065 Main Ram Def/Major Division
Horizontal - 0.2 Sec/Major Division
Input - 3 H_z

Figure 39. Channel Three Failure Removal Characteristic
Fail Safe Mode - Positive Input
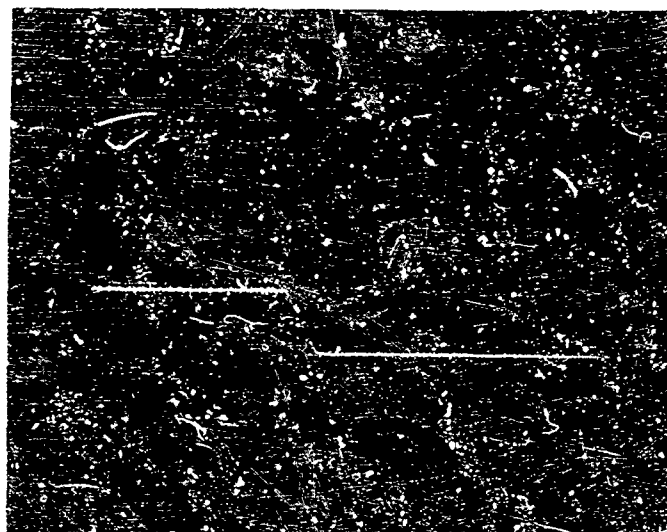
50

Fail Safe Mode
Channels One & Two - Failed Electrically
Channel Three - Failed Hardover Negative
Vertical - .180 Main Ram Def/Major Division
Horizontal - 0.5 Sec/Major Division
Input - None
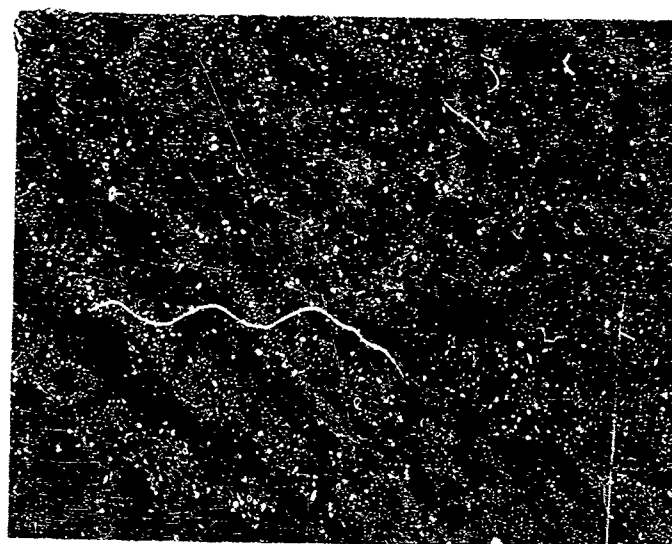
Fail Safe Mode
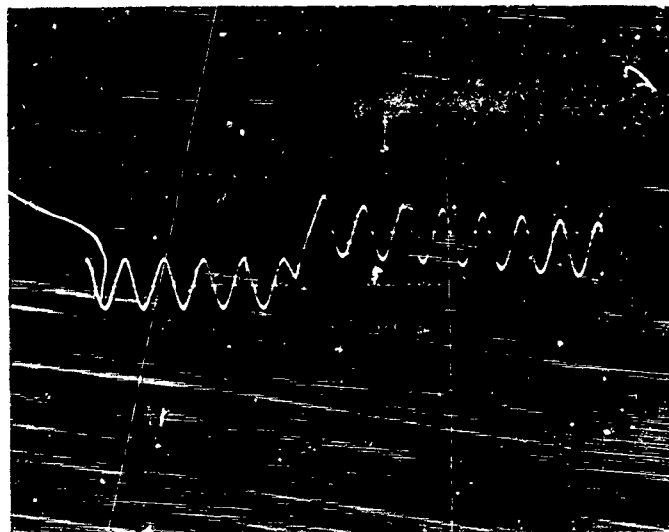Channels One & Two - Failed Electrically
Channel Three - Failed Hardover Negative
Vertical - .065 Main Ram Def/Major Division
Horizontal - 0.2 Sec/Major Division
Input - 3 H_z

Figure 40.   Channel Three Failure Removal Characteristic
   Fail Safe Mode - Negative Input

51

1.6 Problems Encountered During Test Evaluation

During the testing evaluation, the model channel
would consistently overheat, causing the simulator to
transfer to the fail operate mode from the dual fail
operate mode. In order to keep the model channel con-
sistently engaged, the cover was removed from the model
chassis and a small cooling fan was used to cool the unit.

The actuator low level (strokes less than $\pm$ .050
inches) threshold characteristics prevented making low
amplitude, low frequency measurements. The dynamic res-
ponse below 1 cycle and .05" deflection was erratic to
the point that dynamic measurements were prevented.

1.7 Conclusions

As stated in the AFFDL-TR-69-9 (Report on the Devel-
opment of the Sperry System) the experimental laboratory
model was designed to demonstrate the feasibility of the
particular redundant system mechanization. As a demon-
strator, the unit operated satisfactorily with few prob-
lems.

The surface deviations with injected failures varied
with the redundancy operating mode. In the two fail operate
mode, the maximum deviation was 3.25%. In the fail operate
mode, the maximum deviation was 6%. In the fail safe mode
the maximum deviation was 18.5%.

The apparent actuator dynamic threshold for linear
operation appeared to be significant enough (approximately
2.8%) to require improvement if the performance potential
of the particular fly-by-wire mechanization is to be rea-
lized. This high dynamic threshold (probably caused by
seal friction in the servoram linkage) would prevent low
level dynamic control signals from being faithfully re-
produced at the actuator output.

The preflight checkout sequence operated satisfac-
torily; however, the sequence of test failures was not com-
plete enough to more than nominally check the operating
conditions of the unit, and would require expansion for
an actual flight unit.

The degradation of servoram response with injected failures was somewhat greater than anticipated for the force sharing type of mechanization used. The extent of the degradation was probably greatly influenced by the friction and seal loading of the servoram and although it probably could have been improved, it does point out that area as a critical design point of the mechanization.

The general response measurements documented reflected results similar but not identical with those run by Sperry during the development testing. Slightly more performance degradation than that measured by Sperry was encountered in the fail safe mode and channel select modes of operation. This probably indicated a slight change in the operating condition of the simulator between the two periods.

1.8 Recommendations

If the Sperry system were to be used in flight application, the electronics would require some modification in order to pass the high environmental thermal requirements in aircraft.

Since in normal operation, the electronic system would be run using three different phases of electrical power, the system should be evaluated with this operating condition. Because the unit is designed to operate on three phase electrical power and can be incorrectly connected to the electrical power, it would appear worthwhile incorporating into the demonstrator circuitry to protect the electronics from the 100% overvoltage conditions possible with incorrect connection to a three phase electrical source.

In view of the use of the simulator as a laboratory model, the electronics were not particularly accessible. Although the packaging would have good application in production hardware, the accessibility of the electronics did not lend itself to convenient test measurement and/or trouble shooting. For future testing, convenient test points should be permanently incorporated into the simulator.

Because of the apparent effects of seal friction

53

(high dynamic threshold and change of main ram response with change in failure mode), it is recommended that the servoram seal friction be reduced. This could be accomplished either by a seal type change to a lower friction seal (Bal seal) or equivalent, or carrying out mechanical redesign of the mechanization to improve the "drive area" to "seal force" relationship.

2. VICKERS MOTORPUMP EVALUATION

2.1 Introduction

The Vickers Motorpump was submitted for evaluation as
a potential back up hydraulic power source for use in cri-
tical or sensitive portions of an aircraft flight control
system. The device would be mounted internally within the
airframe and automatically actuated or connected to a pre-
selected portion of the aircraft hydraulic system upon
failure of the on board hydraulic sources. The motorpump
would provide short term, emergency, hydraulic power and
limited handling characteristics to enable the pilot to
maneuver the aircraft to a safe area.

Fig. 41 is an illustration of the Vickers Model
MPEV3-044-2 motorpump submitted for evaluation.

2.2 Device Description

The Vickers Motorpump is a variable displacement in-
line piston pump positioned coaxially on a common driven
shaft with a single stage centrifugal boost pump as illus-
trated in a typical design shown in Fig. 42.

The pumps are driven by a totally enclosed 10.0 HP,
3 ϕ. 400 H_z air cooled induction motor which is equipped
with an external fan and finned case. The centrifugal
boost pump draws hydraulic fluid from the reservoir and
increases the oil pressure sufficiently to prevent cavi-
tation of the piston pump at low fluid temperatures.

The flow from the piston pump is proportional to the
yoke angle. The yoke is positioned by an actuator piston
which is alternately connected to output pressure or case
drain as determined by the valve action of a spring loaded
pressure compensator piston as shown in Fig. 43.

The movement of the actuator piston is mechanically
coupled to the yoke such that the delivery volume is inversely
related to the developed pressure within the normal control-
lable range (less than maximum displacement) of the variable
displacement pump.
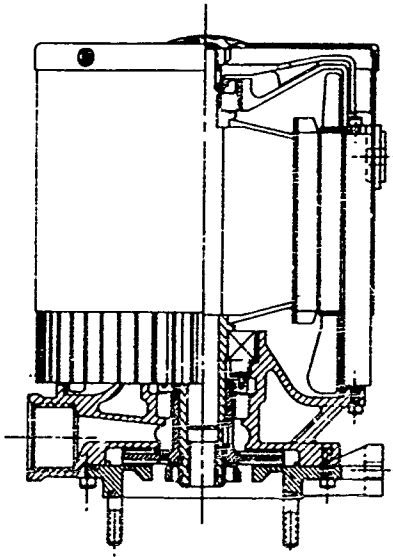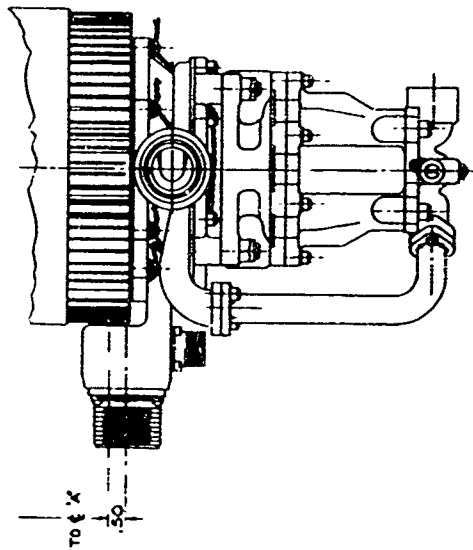
TYPICAL CENTRIFUGAL BOOST PUMP SECTION
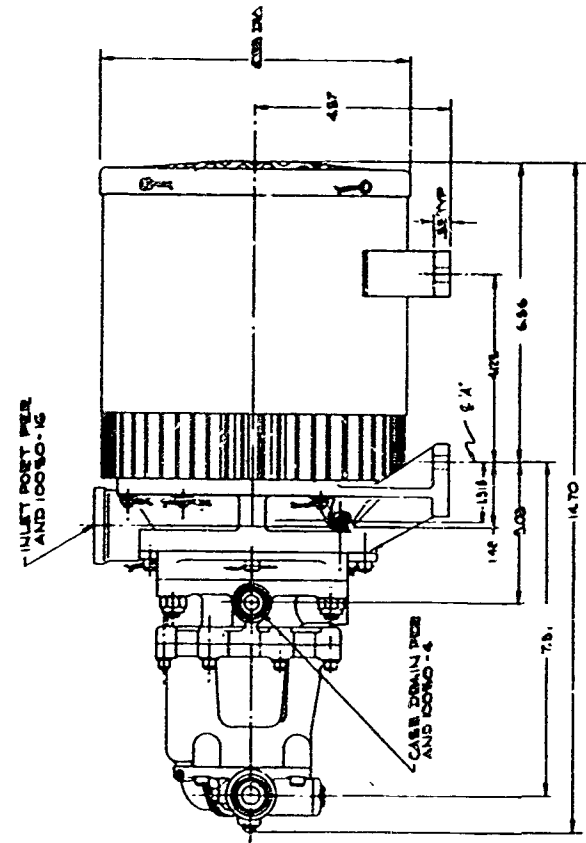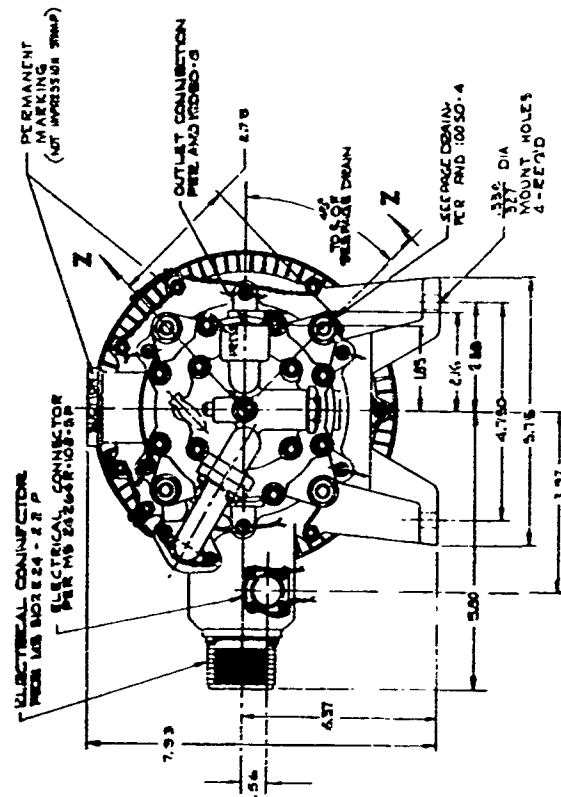
Figure 41. Vickers Motorpump Model MPEV3-044-2

56
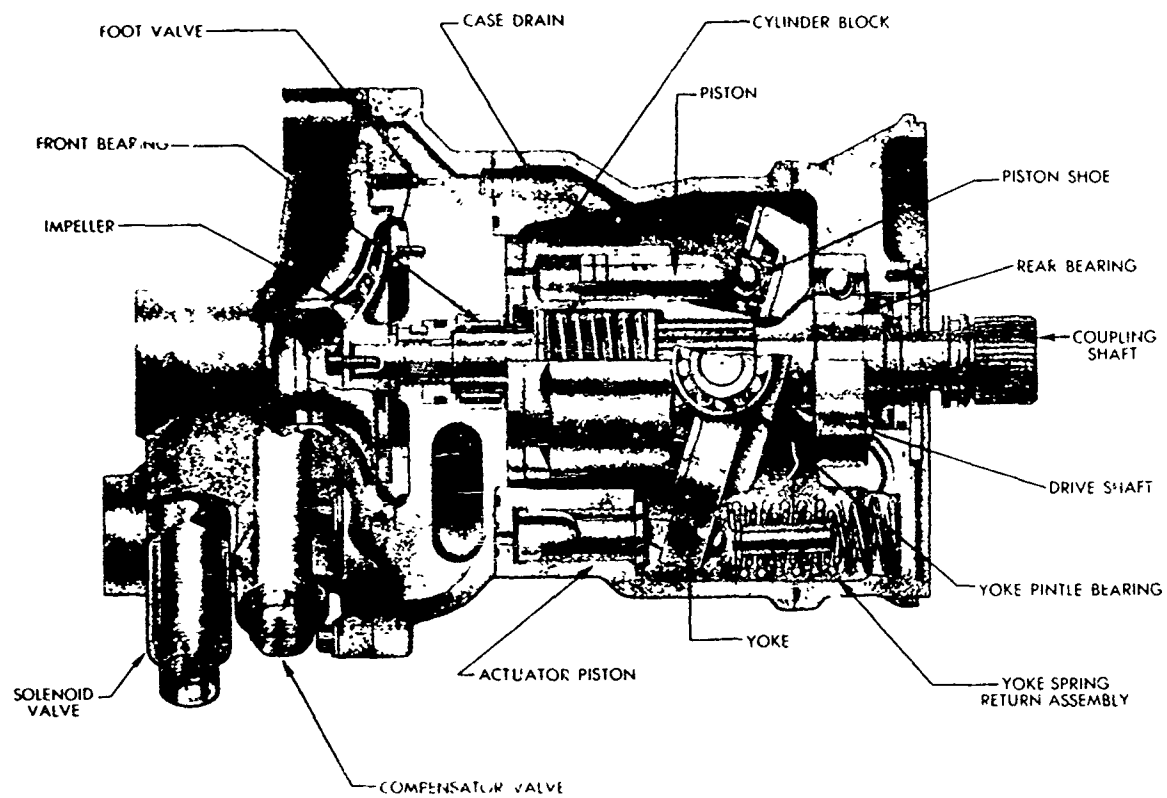
Figure 42. Typical Motorpump Design

(Vickers Model MPEV3-044-2)

57

COMPENSATOR VALVE

TO TANK

P CASE

OUTLET

HIGH PRESSURE

P_s

P_c

COMPENSATOR
VALVE SPRING

PUMP YOKE

DRIVE SHAFT

INLET

LOW PRESSURE

P_i

PRESSURE ADJUSTMENT

YOKE ACTUATING CYLINDER
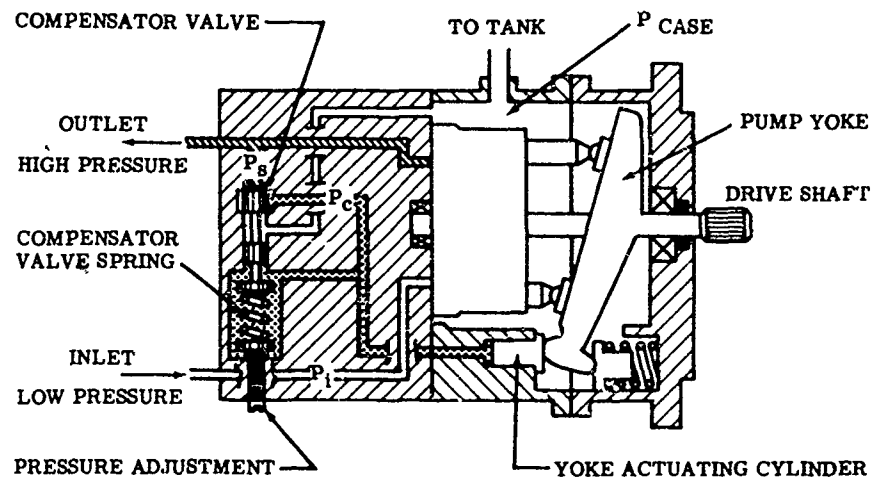
SCHEMATIC SKETCH OF PRESSURE COMPENSATED PUMP
(DIFFERENTIAL TYPE)

Figure 43. Pressure Compensator Mechanism

(Vickers Model MPEV3-044-2)

58

2.3 Test Description

There is a vast number of airframes and related hydraulic circuits to which the Vickers Motorpump could be adapted. Therefore, it was necessary to establish a limited general test program to evaluate the innate hydraulic, electrical, and mechanical characteristics of the device rather than the application of the Vickers Motorpump package to a specific user requirement.

The following series of tests were selected by analysis of possible failure modes and method of application of the device:

2.3.1 Determine the pressure-flow (P-Q) capabilities of the motorpump package under nominal specified power input conditions.

2.3.2 Determine the tolerance of the device to reduced input voltage conditions at various flow rates.

2.3.3 Determine the temperature rise characteristics of the Vickers Motorpump unit at various hydraulic power output levels.

2.3.4 Determine the start up characteristics of the motorpump combination at various flow rates and power input conditions.

2.3.5 Determine the operating characteristics of the motorpump combination connected to an aerodynamically loaded (simulated) hydraulic actuator.

The test stand shown in Fig. 44 was assembled to obtain empirical data from the Vickers Motorpump assembly. The motorpump receives hydraulic fluid from a one gallon sealed reservoir. The reservoir was pressurized to prevent foaming and cavitation of the pumps due to test stand flow restrictions. During tests 2.3.1 through 2.3.4 the pressurized fluid from the pump was throttled through a bypass valve to reservoir return. The fluid was directed to the F-4 stabilator actuator during test 2.3.5 and the bypass valve was closed.
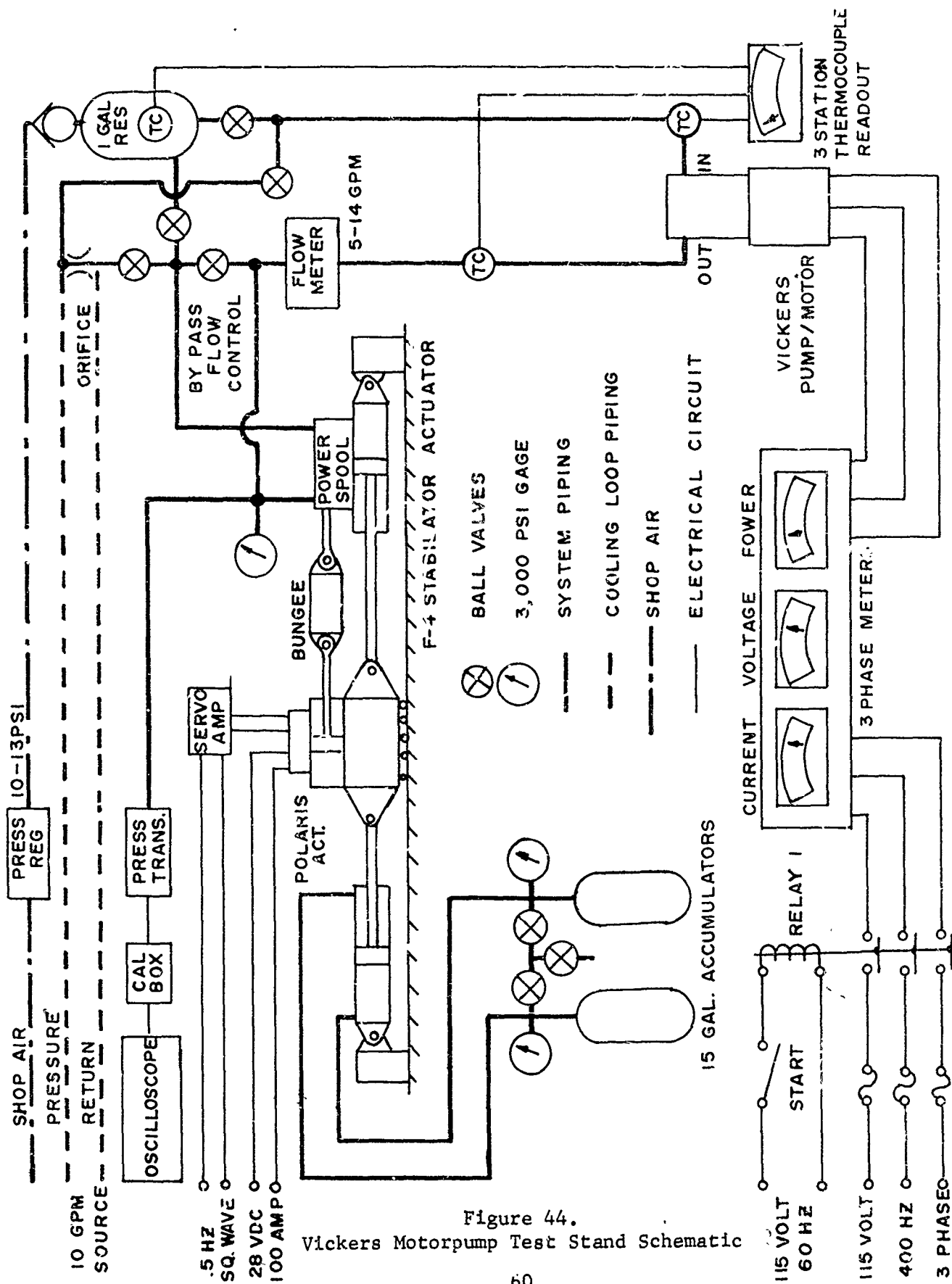
Figure 44.
Vickers Motorpump Test Stand Schematic

60

The electrical input to the motor was monitored. Applied voltage, current and power consumption data was recorded. System pressures were monitored visually at several points with pressure gauges and a pressure transducer was installed to record system pressure changes with an oscilloscope camera.

An auxillary hydraulic source equipped with a large reservoir and oil coolers was connected to the test stand hydraulic system to provide recirculating cooling to rapidly reduce the high system temperatures that were developed during test stand operation. The cooling flow was obtained from across a low pressure drop orifice which developed a differential pressure of 35 psi at full flow from the auxillary hydraulic source. Between tests flow through the motorpump was intermittantly cycled between the reservoir and the auxillary system to remove the heat generated by prolonged evaluation testing.

The (simulated) aerodynamically loaded actuator portion of the test stand is shown in Fig. 45. This mechanization utilized two F-4 stabilator dual tandem servoactuators. The control valve was removed from one unit and the hydraulic cylinder portion of the actuator was fitted with a manifold plate. Each side of the ram end of the actuator was connected to a 15 gallon depressurized accumulator. The accumulator, actuator, cylinder, and connecting lines were then filled with hydraulic fluid and pressurized several times to remove the entrained air. The actuator was then centered and the interconnecting valves were closed. The liquid spring thus created utilized the compressibility of the hydraulic fluid to generate a linearly increasing simulated aerodynamic load of 18,000 pounds at full stroke of three inches in either direction from the center position.

The other F-4 actuator was connected to the Vickers Motorpump assembly. The actuator was joined to the liquid spring with a slide block which rode cylindrical ways attached to a very rigid base support. The other ends of the actuators were restrained in clevis block that were rigidly attached to the base support.

Inputs to the Vickers Motorpump powered F-4 stabilator
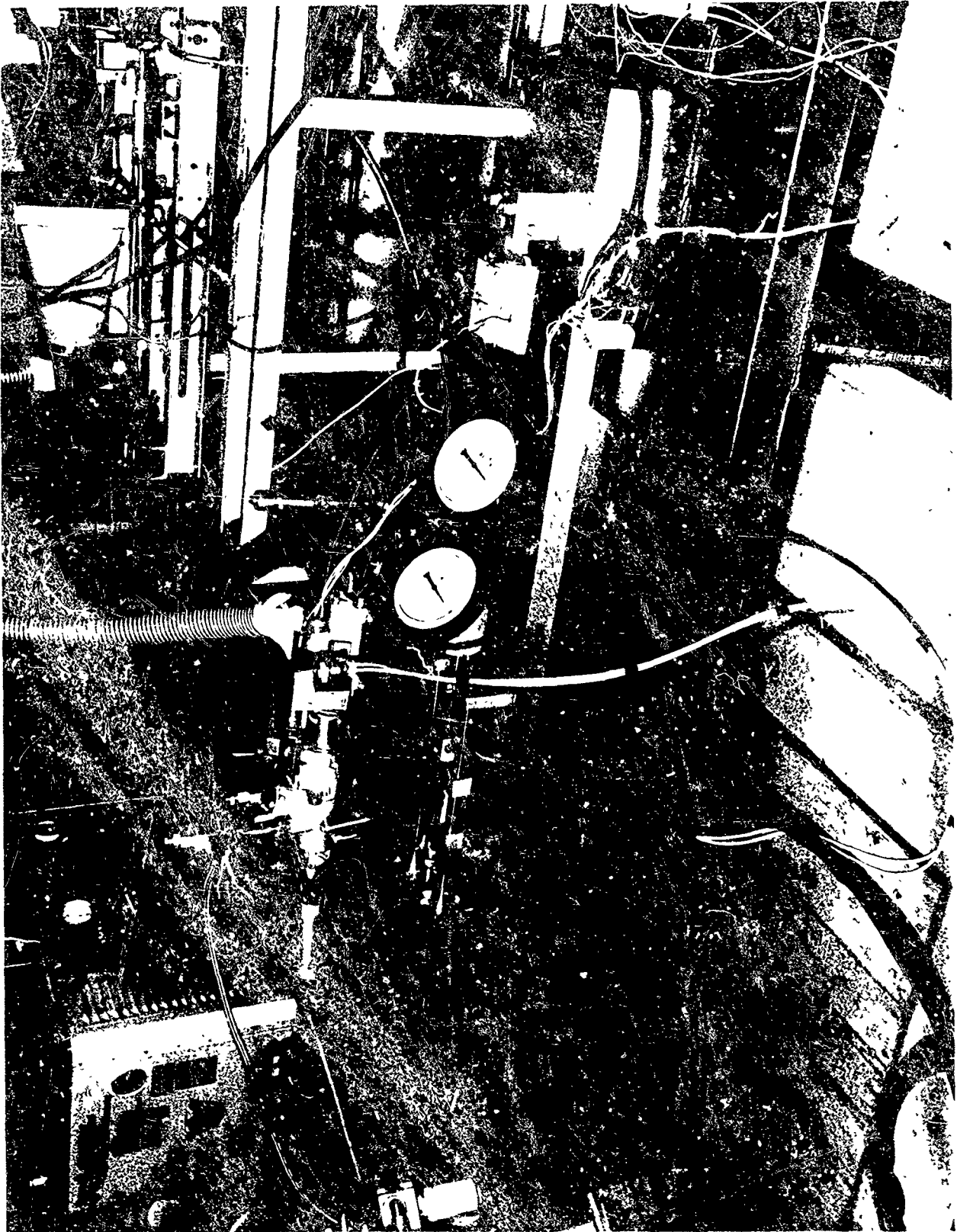
Figure 45. Loaded Actuator Motorpump Test Setup

actuator were generated by a Hydraulic Research and Manufacturing Company integrated package Polaris actuator identical to the unit evaluated and reported in another section of this report. This actuator was utilized because of its small size and greater slewing capability than the F-4 stabilator actuator.

The Polaris actuator was attached to a riser block from the slide that connected the F-4 actuator to the liquid spring. A closed loop position servomechanism was thus formed because the Polaris actuator position inputs were effectively cancelled by movement of the Polaris actuator body relative to the F-4 actuator.

A spring preloaded, overstroke cartridge was connected between the Polaris actuator output and the differential output linkage of the F-4 stabilator actuator to prevent damage to either mechanism in the event the coupled dynamic response of the actuators became sufficiently out of phase to cause the F-4 stabilator actuator differential input linkage to reach the limit stops.

2.3.1 Nominal Pressure - Flow Characteristics

The Vickers Motorpump assembly was mounted in the test stand and connected to the hydraulic and electric power sources as shown in Fig. 46. The unit was operated under full bypass flow conditions (zero indicated pressure) and the line voltage was adjusted to 208 volts, leg to neutral on each phase.

The bypass valve was progressively closed to throttle the flow in one gallon increments from 10 GPM to 1 GPM and the developed line pressure was noted at each increment. The initial test was performed at 100°F oil temperatures and repeated at 250°F oil temperatures.

2.3.2 Reduced Input Voltage Tolerance

The Vickers Motorpump was operated in one gallon incremental flow rates from zero to 10 GPM. The input voltage was gradually reduced and the flow rate was maintained at a

63
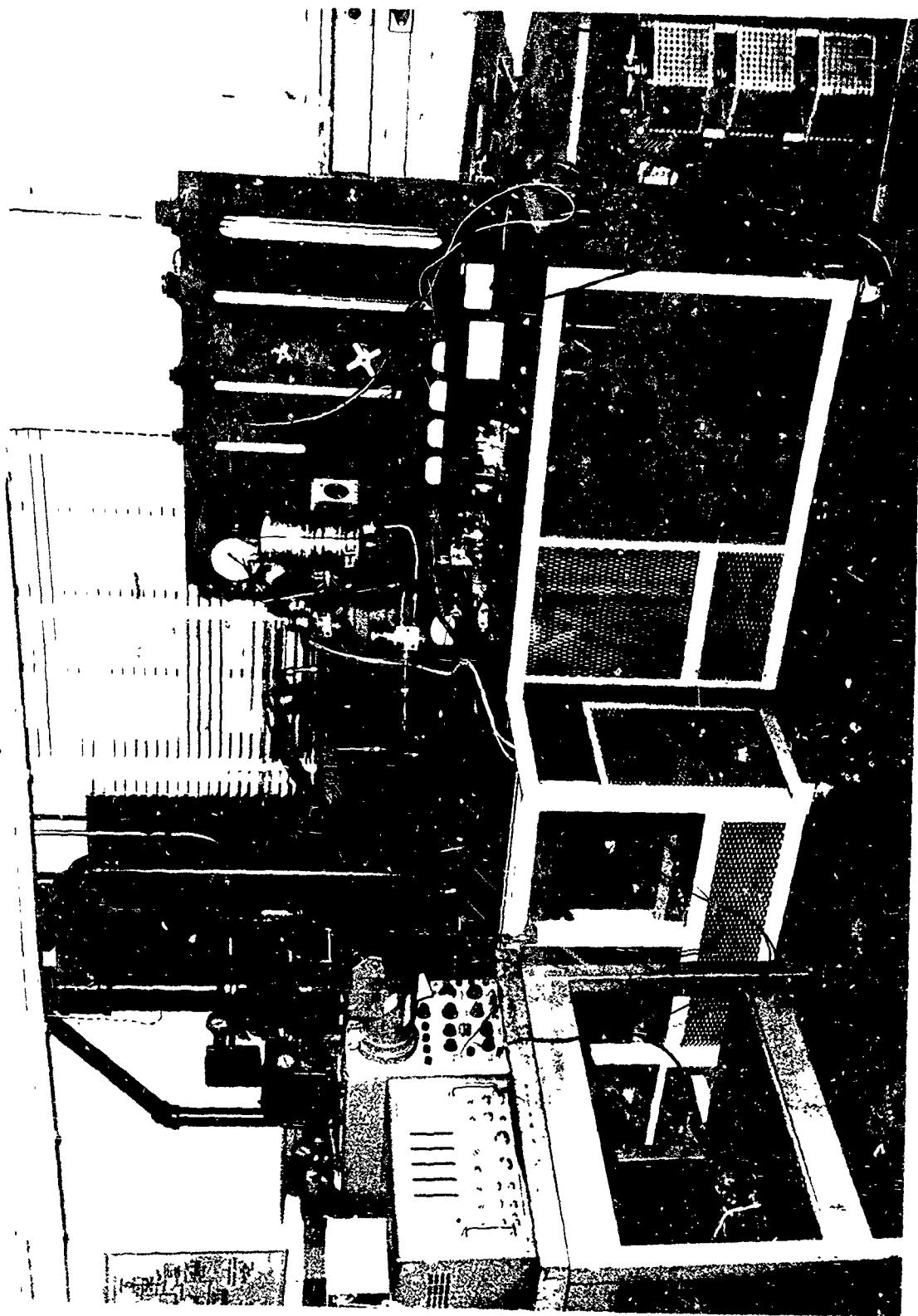
Figure 46. Vickers Motorpump Test Stand Pictorial

constant value by readjusting the bypass valve. Detrimental
effects such as pressure instability, motor stall or exces-
sive motor heating were recorded.

2.3.3 Temperature Rise Characteristics

The Vickers Motorpump assembly was operated at nominal
input power requirements. The temperature rise, time his-
tory of the pump inlet, pump outlet and reservoir were re-
corded at one minute intervals for each one gallon change
in flow rate from zero to 10 GPM. The pressure head was
allowed to vary in accordance with the nominal pressure-
flow relationship. The test was halted when any one of the
three temperature observation points exceeded 280°F.

2.3.4 Start-Up Characteristics

The Vickers Motorpump assembly was operated in one
gallon incremental flow rates from zero to 10 GPM. The
operating point on the P-Q curve was established under nom-
inal input voltage conditions and the motorpump was stopped
and restarted. The time interval required for the devel-
oped pressure to reach a maximum level and any associated
pressure transients were recorded by photographing the os-
cilloscope trace of the pressure transducer output.

The input voltage was then progressively reduced in
ten volt steps and the output flow was maintained at the
maximum regulated rate of 8 GPM. The Vickers Motorpump
was stopped and restarted at each increment of applied vol-
tage and a photograph of the resulting pressure rise wave-
form was obtained.

The oscilloscope was set for triggered sweep and a
trigger pulse was obtained from a capacitive coupling to
one of the motor terminals downstream from the solenoid
operated disconnect switch. Therefore, the scope sweep
started when the first positive cycle of line current was
applied to the motor.

2.3.5 Loaded Actuator Performance Characteristics

The Vickers Motorpump assembly was connected to the
driving F-4 stabilator actuator and the bypass valve was
closed. The Polaris actuator was driven at a 0.5 H_z rate

from a square wave generator. The frequency of the input signal to the actuator was selected as representative of the average rate of hardover inputs that a pilot could generate at the control stick if he is working against the "Q" spring load. The amplitude of the input signal was adjusted to cause the F-4 stabilator actuator to follow the Polaris input with a stroke of $\pm$ 1, $\pm$ 2, $\pm$ 2-1/4 inches, as measured at the slide that connects the actuator to the liquid spring. The stroke was limited to $\pm$ 2-1/4 inch by the selected cycle rate of 0.5 H_z and the limited flow from the motorpump.

Temperature time history of the Vickers pump inlet, pump outlet and the reservoir were recorded in one minute intervals until any one of the temperatures measured exceeded 250°F.

2.4   Test Results

This section of the report delineates the results of the five test series that were performed on the Vickers Motorpump Assembly.

2.4.1   Pressure Flow Characteristics

Fig. 47 is a graph of the pressure flow characteristics of the Vickers Motorpump assembly under nominal operating conditions. The pressure compensation within the assembly is capable of maintaining the delivery pressure with moderate droop until the demand flow rate exceeds 8 GPM at 2600 psi. Maximum pump displacement is achieved and any further increase in flow demand results in a rapid drop in developed pressure accompanied by a slight increase in flow due to reduced leakage and improved volumetric efficiency.

The change in the operating curve of the motorpump at elevated temperatures may be attributed to an increase in the clearances in the various leakage paths and a decrease in fluid viscosity.

2.4   Reduced Input Voltage Tolerance

The electric motor driving the Vickers Pumps demonstrates exceptional tolerance to reduced input voltage conditions that occur after the motor is started at nominal

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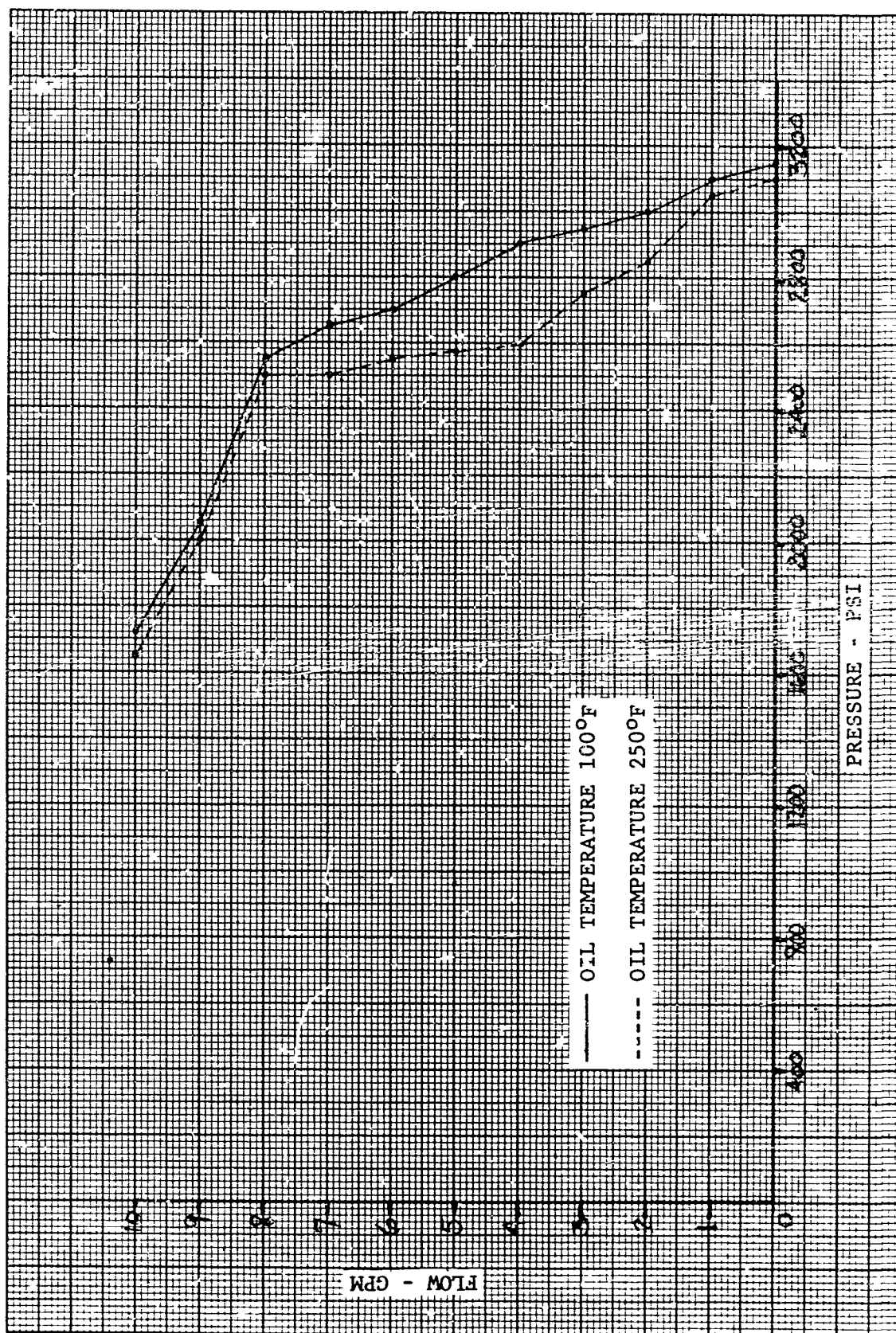
Figure 47. Pressure-Flow Characteristics - Nominal Input

input conditions. Fig. 48 shows that the motor will tolerate as much as a 23% drop in applied voltage at the maximum hydraulic power output point on the operating curve with less than a 10% change in the developed pressure. Fig. 49 and 50 show that an even greater tolerance can be expected at the operating points of 2 GPM at 3000 psi and 10 GPM at 1700 psi. The electrical power requirement at 2 and 10 GPM is proportionally lower than the degraded electric motor capability with reduced input voltage.

2.4.3 Temperature Rise Characteristics

Fig. 51 through 56 represent the temperature-time characteristic of the pump outlet, reservoir and pump inlet at flow rates of 0, 2.0, 4.0, 6.0, 8.0, and 10.0 GPM respectfully. The curves show that the developed temperature after a given interval of time is directly related to the hydraulic power output.

Fig. 51 illustrates an unusual condition in which the pump inlet temperature exceeds the pump outlet. This is the result of continuous agitation by the first stage centrifugal pump impeller of the fixed quantity of fluid entrapped within the centrifugal pump housing under no flow conditions. There is a small (less than one quart/minute) flow of hydraulic fluid through the intermediate seal between the pumps to reservoir return. This flow lubricates and cools the bearings that support the common pump shaft and causes the oil temperature of the reservoir and pump outlet to rise slowly above ambient conditions.

Fig. 51 through 55 show that as the hydraulic power output increases, the time to achieve a limit temperature of 280°F decreases from 33 minutes at 0 GPM to 6 minutes at 8 GPM. Beyond the 8 GPM point on the operating curve, the hydraulic power output decreases very rapidly with increasing flow. Fig. 56 shows that the hydraulic power output at 10 GPM is not sufficient to cause the system to achieve a limit temperature within a reasonable time period in consideration of the intended usage of the Vickers Motorpump assembly.

2.4.4 Start-Up Characteristics

Fig. 57 through 59 show the pressure-time start-up
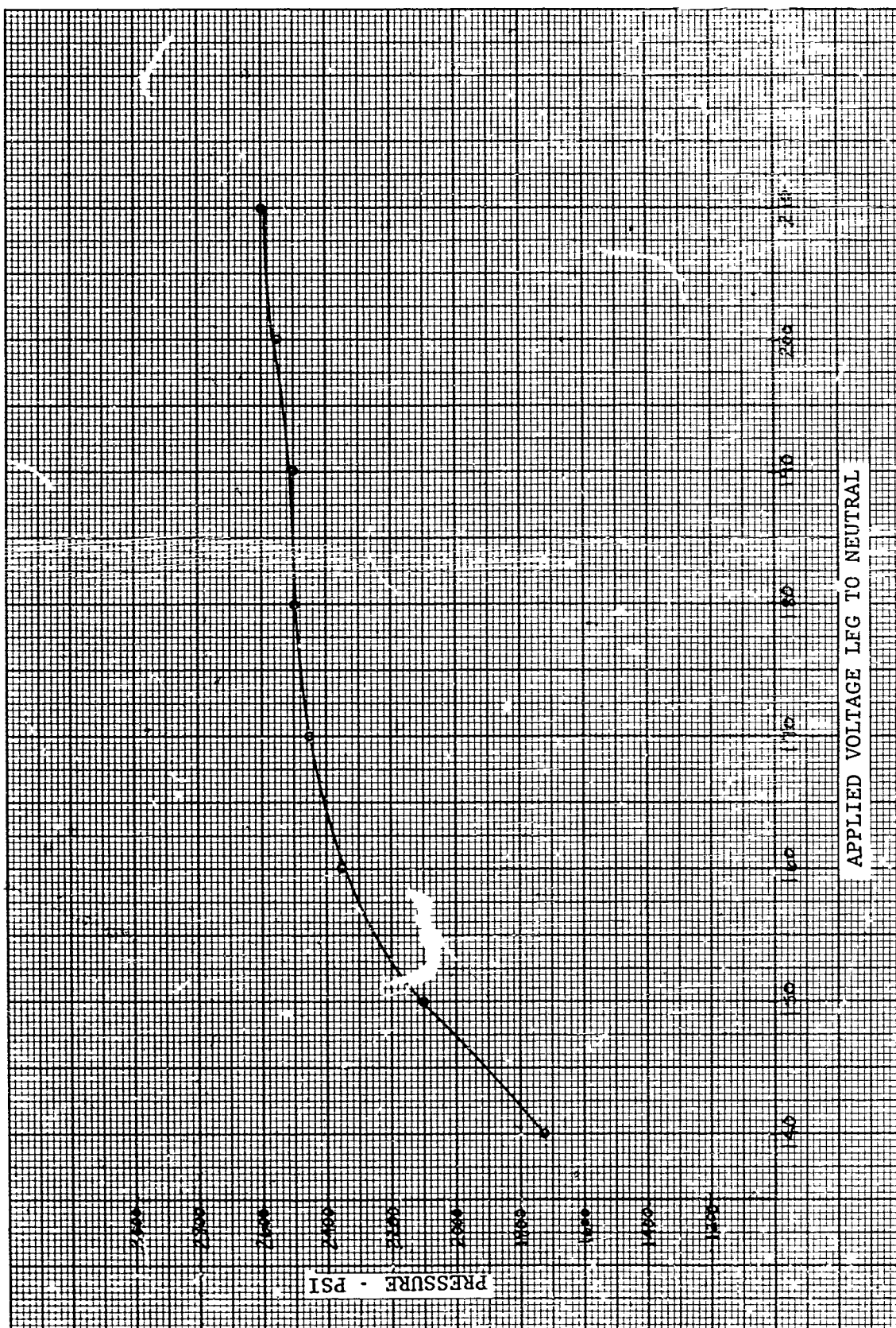
Figure 48. Developed Pressure vs. Applied Voltage -
8 GPM

APPLIED VOLTAGE LEG TO NEUTRAL
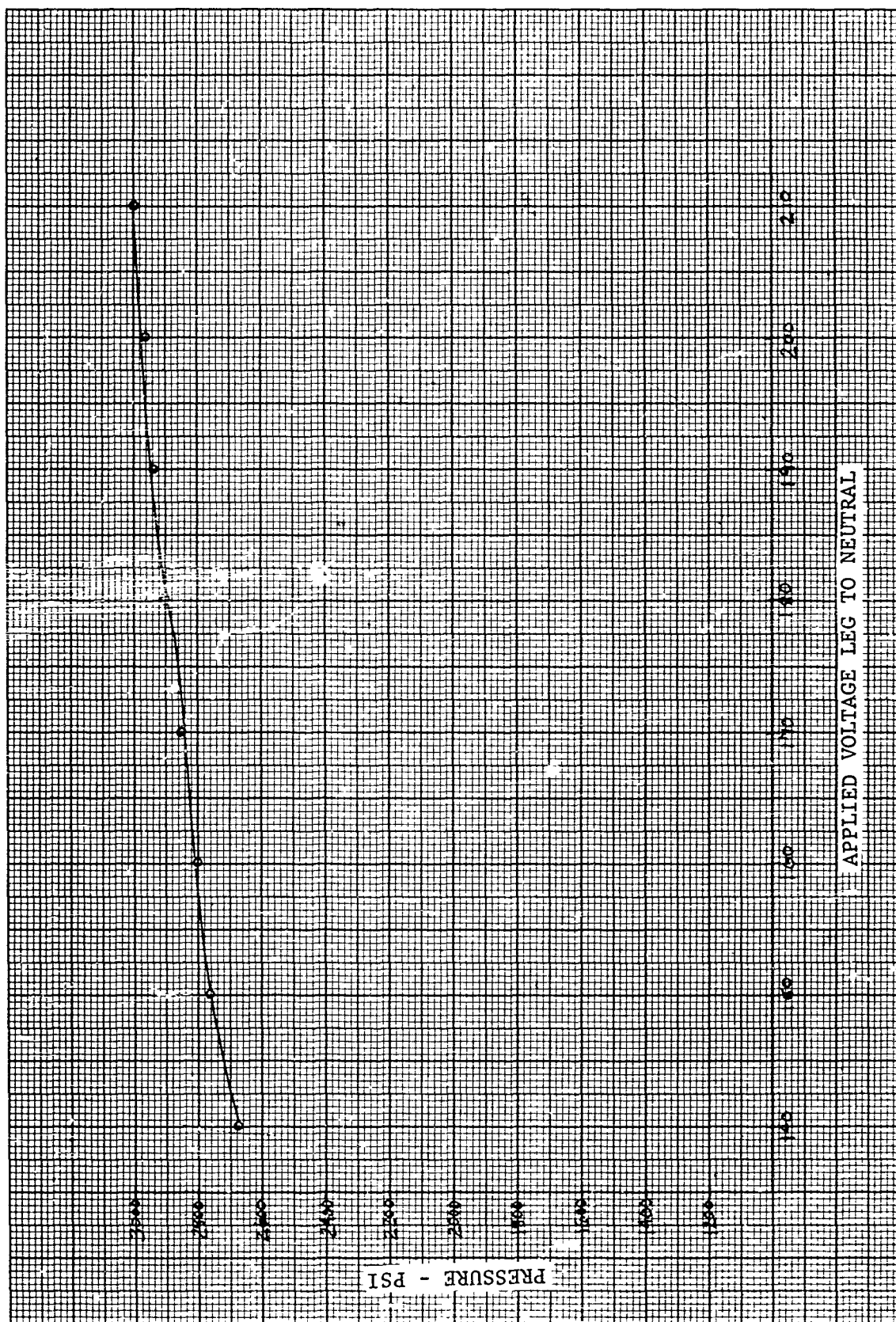
PRESSURE - PSI

Figure 49. Developed Pressure vs. Applied Voltage –
2 GPM

70
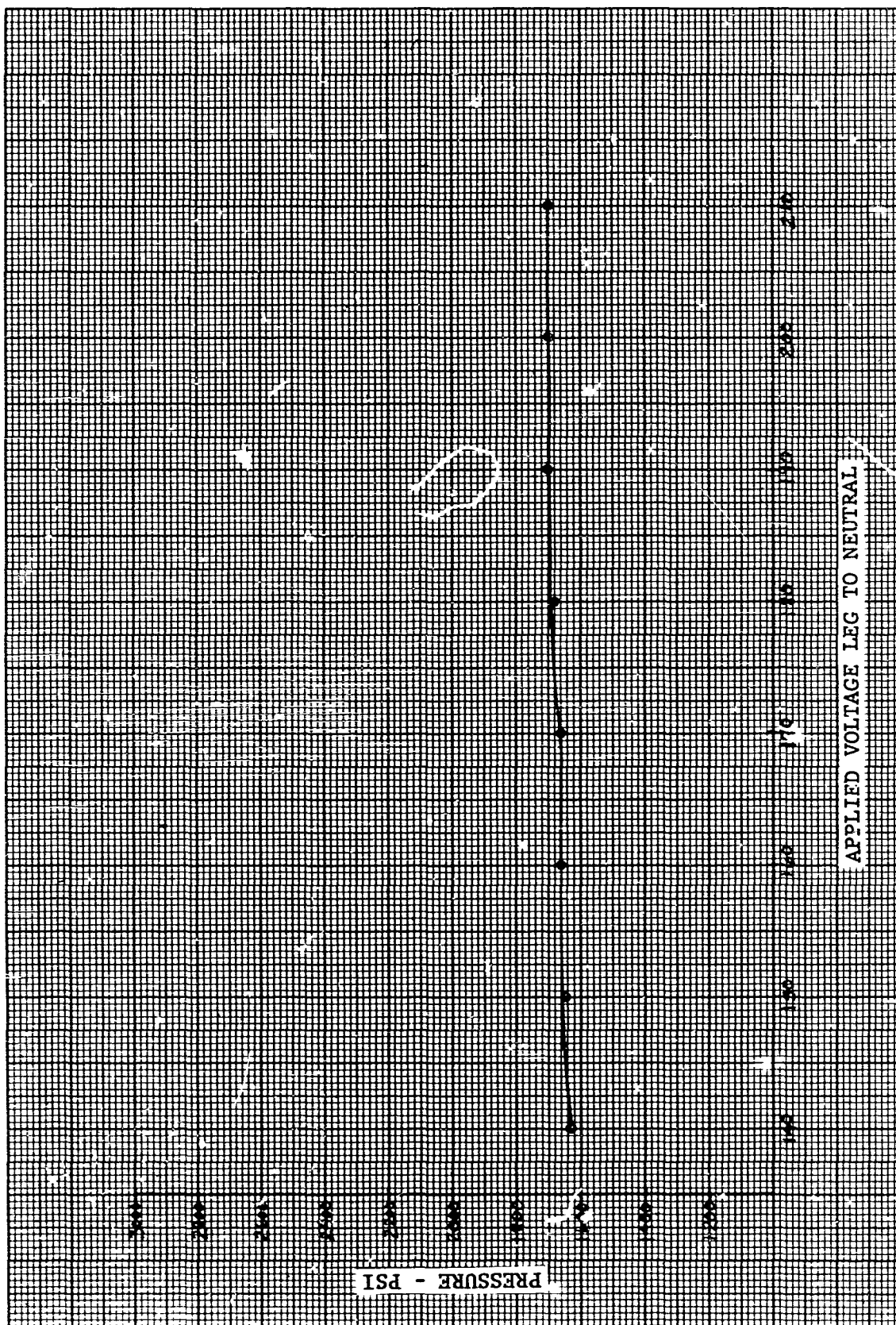
Figure 50. Developed Pressure vs. Applied Voltage -
10 GPM
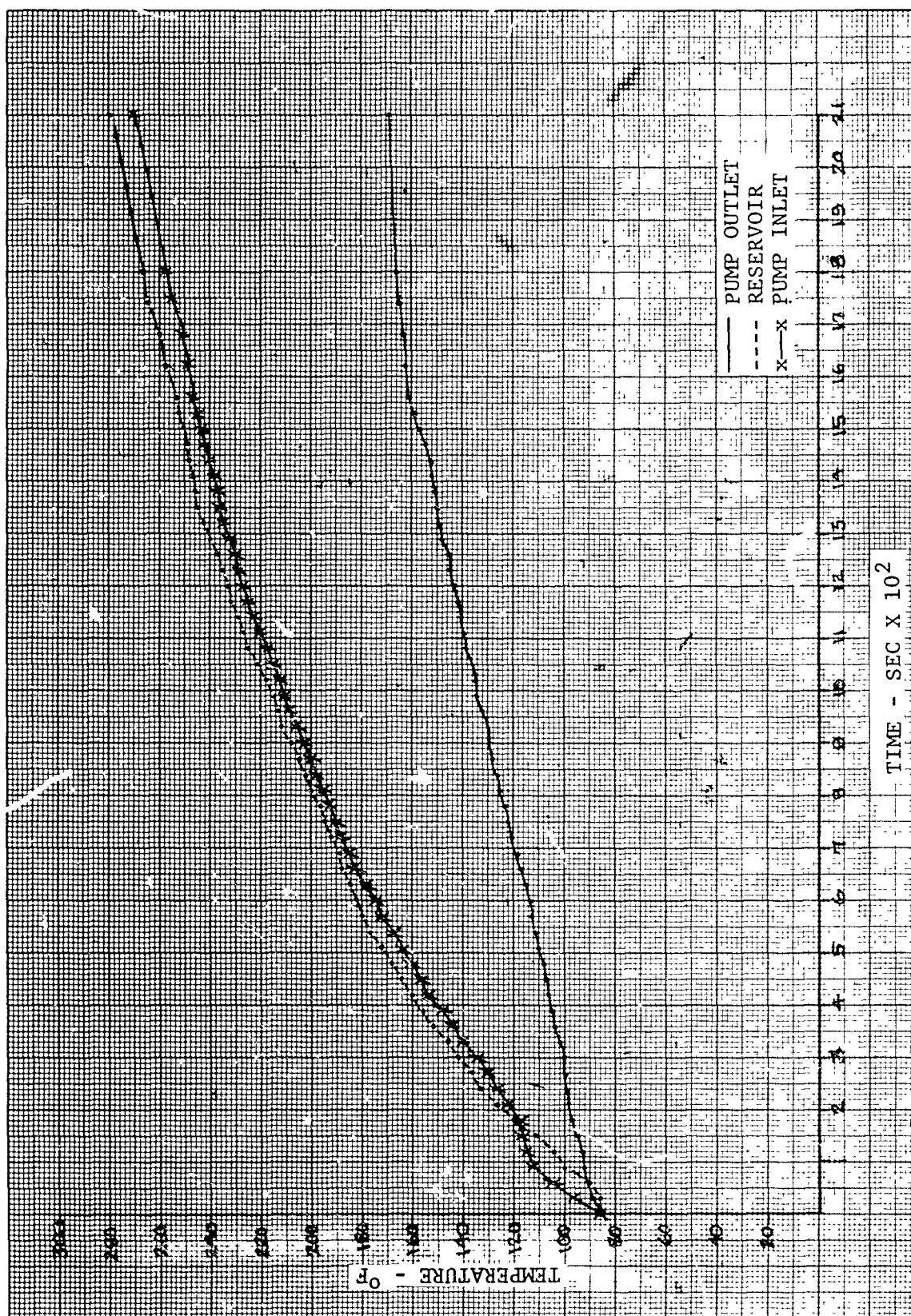
Figure 51. Temperature Time History - 0 GPM

72
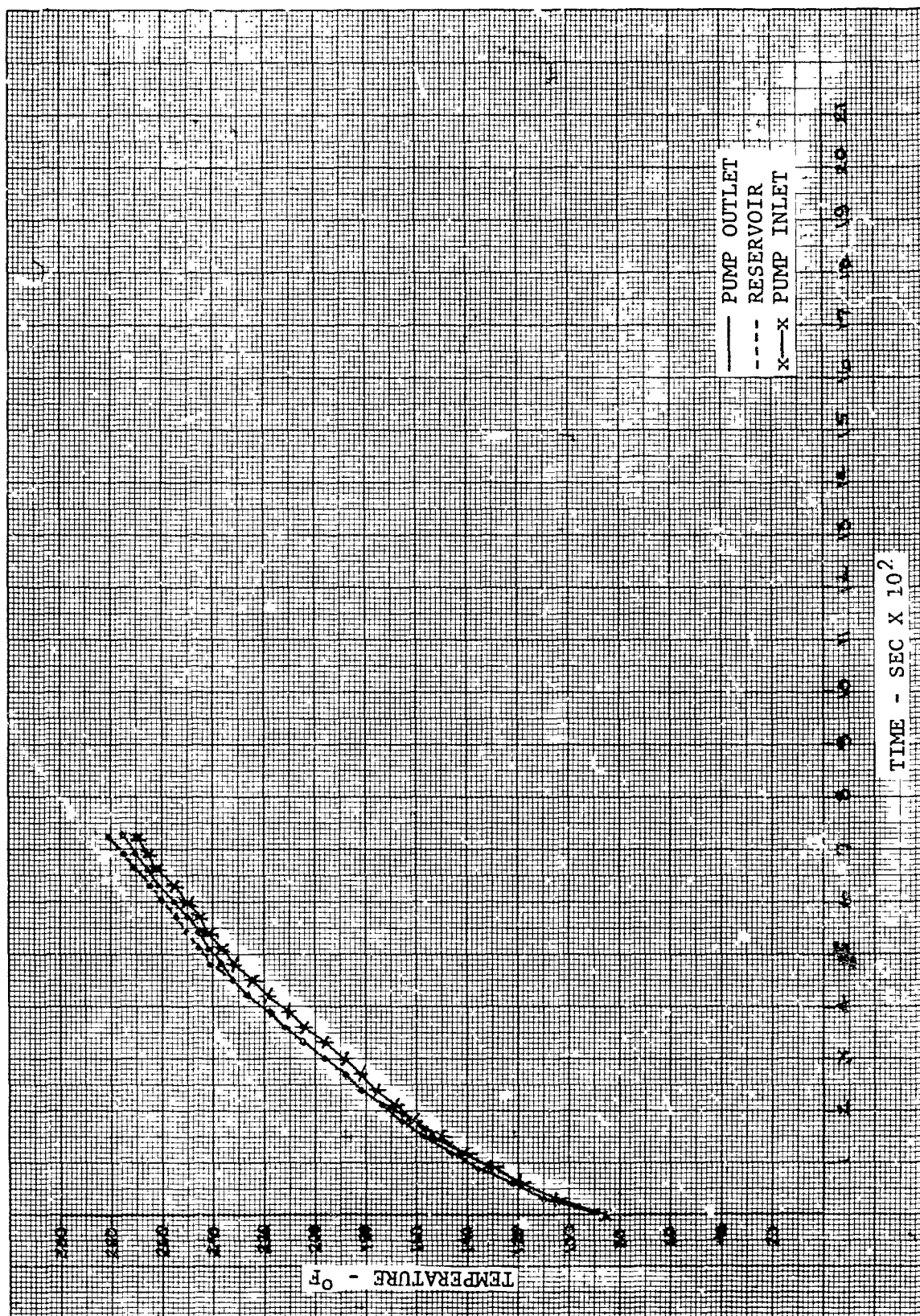
Figure 52. Temperature Time History - 2 GPM

73
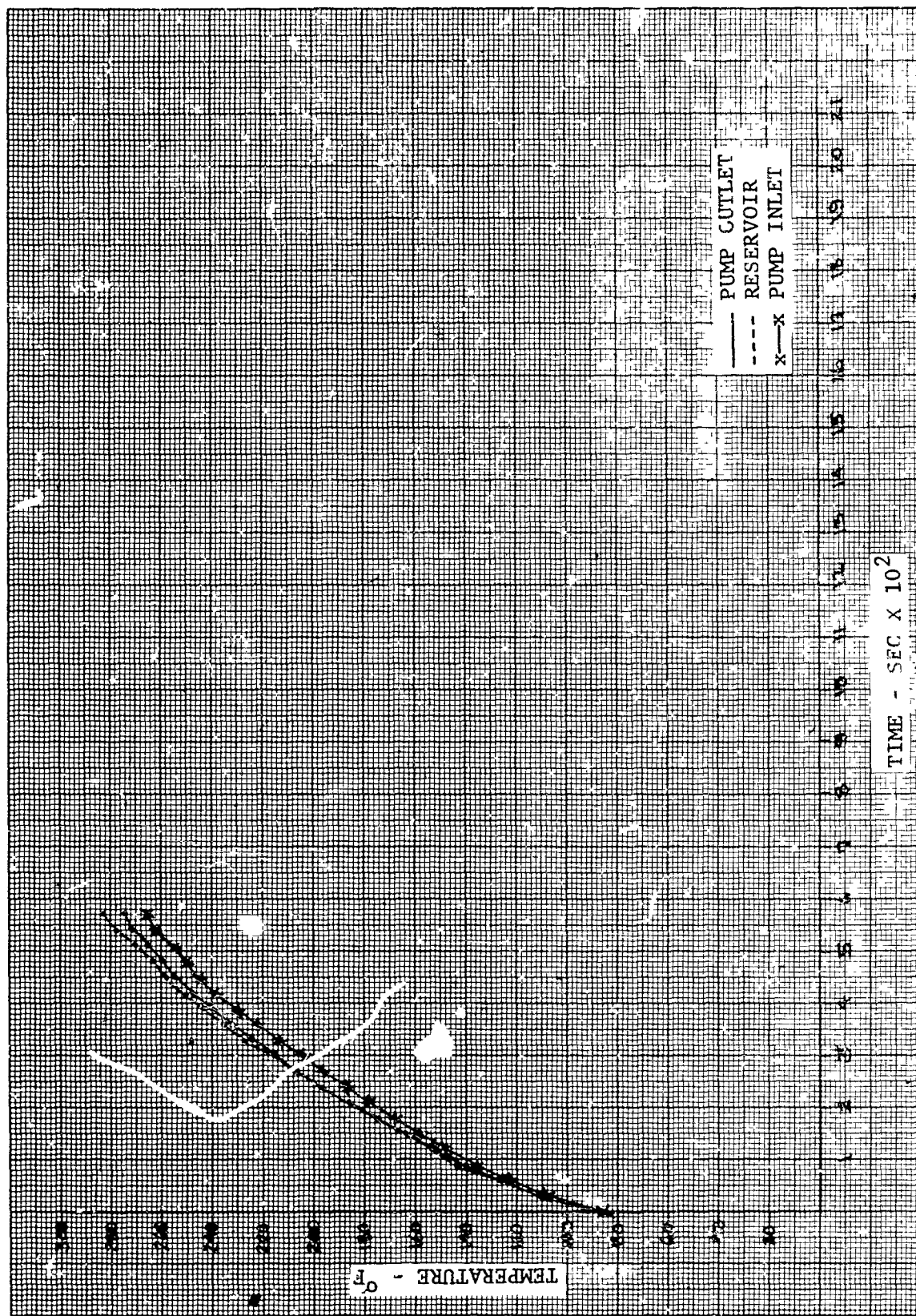
Figure 53. Temperature Time History - 4 GPM

TEMPERATURE - °F

TIME - SEC X 10^2

PUMP OUTLET
RESERVOIR
x—x PUMP INLET
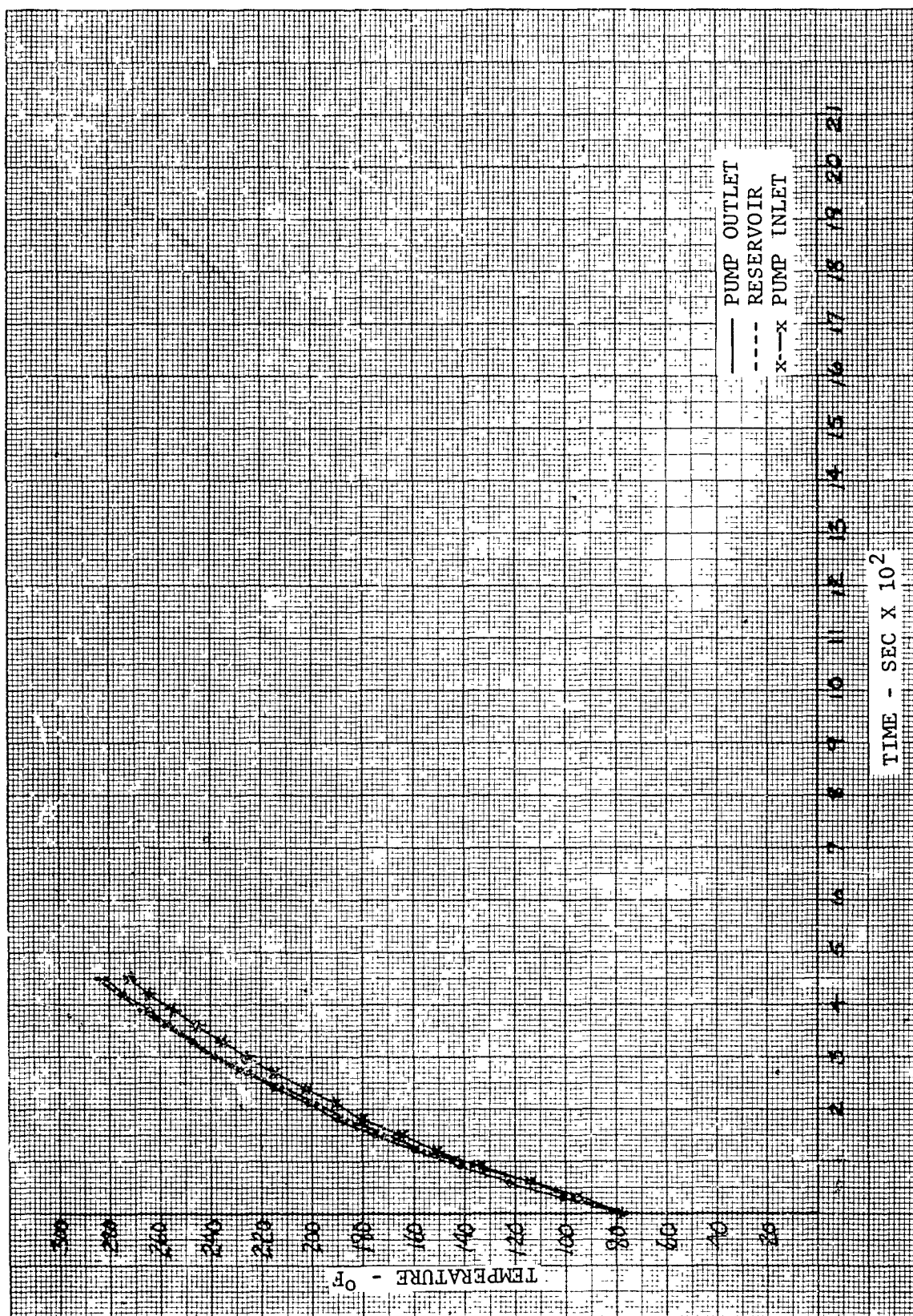
Figure 54. Temperature Time History - 6 GPM
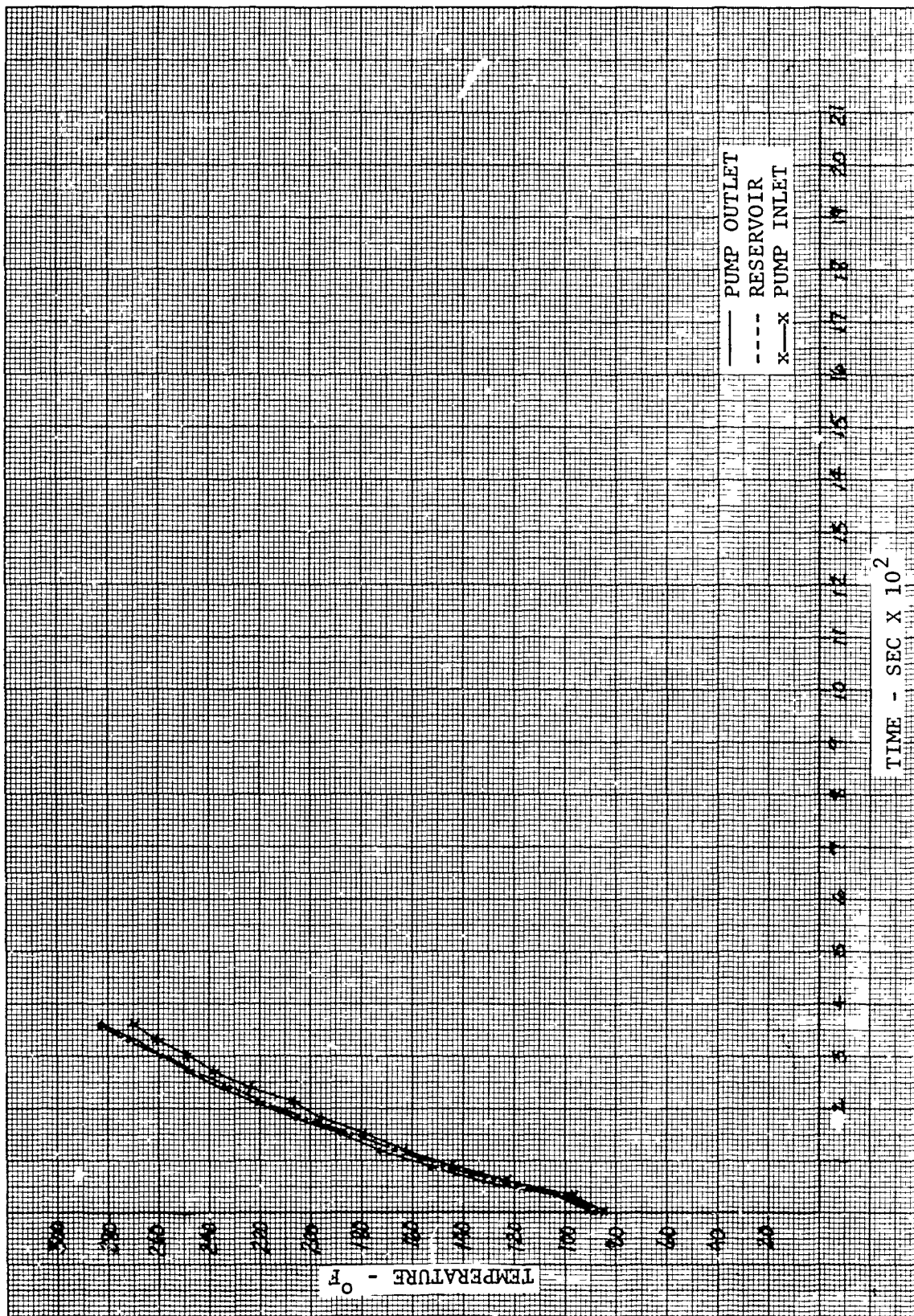
Figure 55. Temperature Time History – 8 GPM
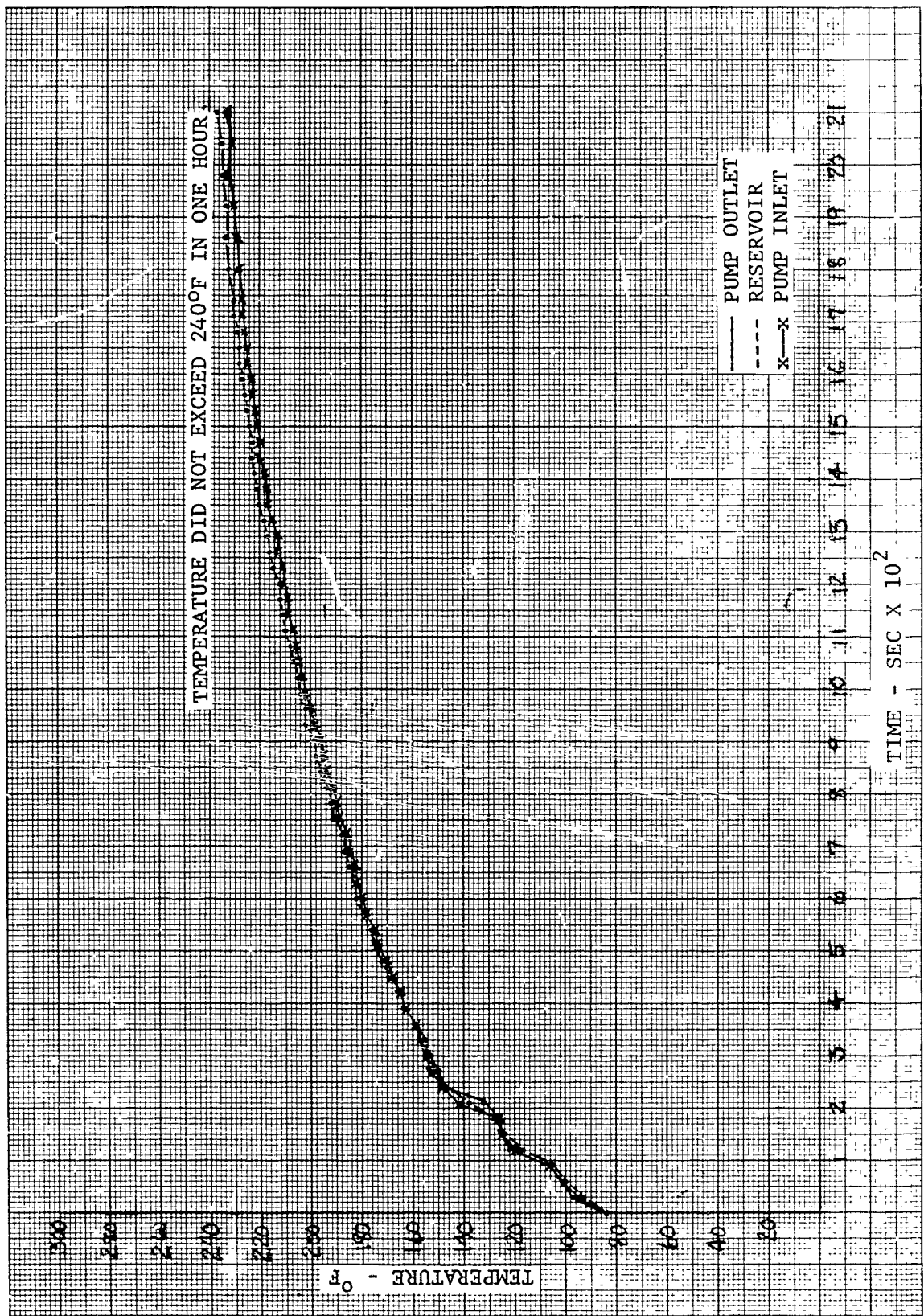
Figure 56. Temperature Time History – 10 GPM
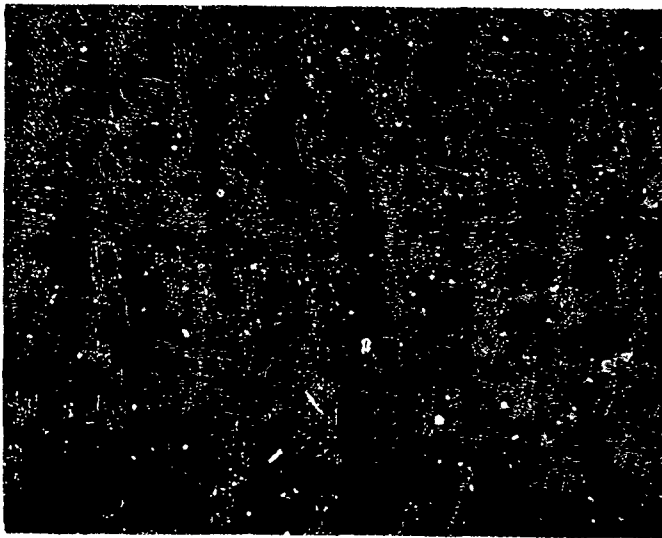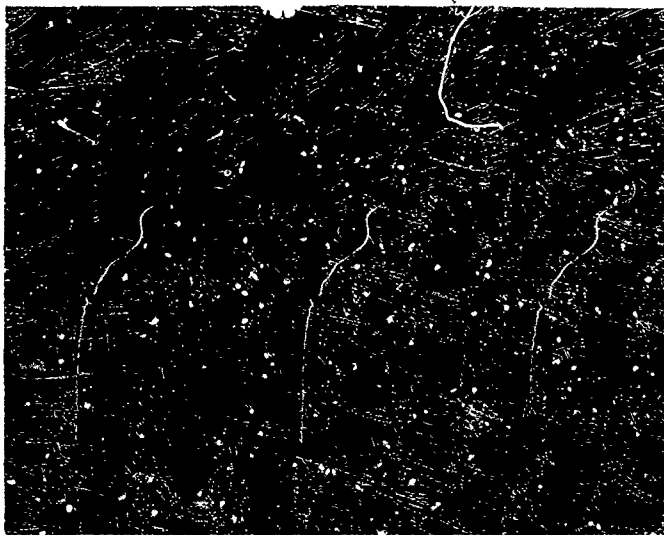
2 GPM

0 GPM

Vertical - 750 PSI/Major Division
Horizontal - 0.2 Sec/Major Division
Time Increasing To Left

Figure 57. Startup Characteristics - 0 and 2 GPM
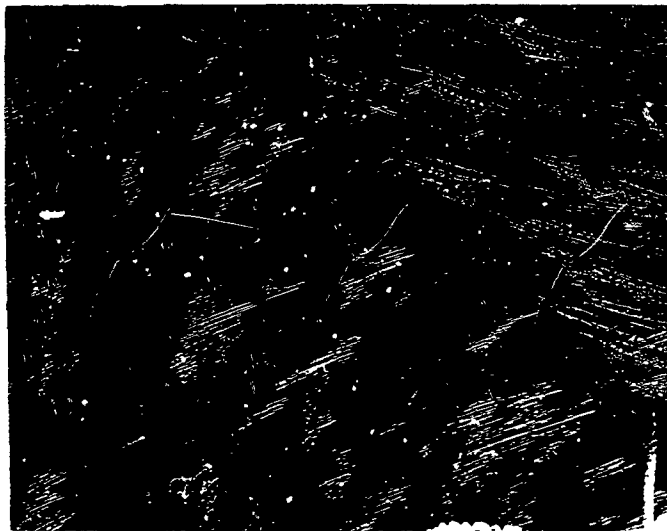
78

6 GPM

4 GPM

Vertical - 750 Psi/Major Division
Horizontal - 0.2 Sec/Major Division
    Time Increasing To Left

Figure 58. Startup Characteristics - 4 and 6 GPM

10 GPM
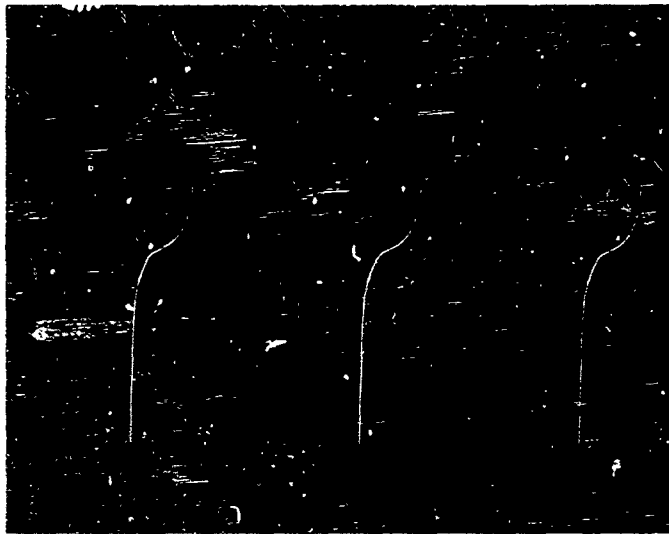
8 GPM
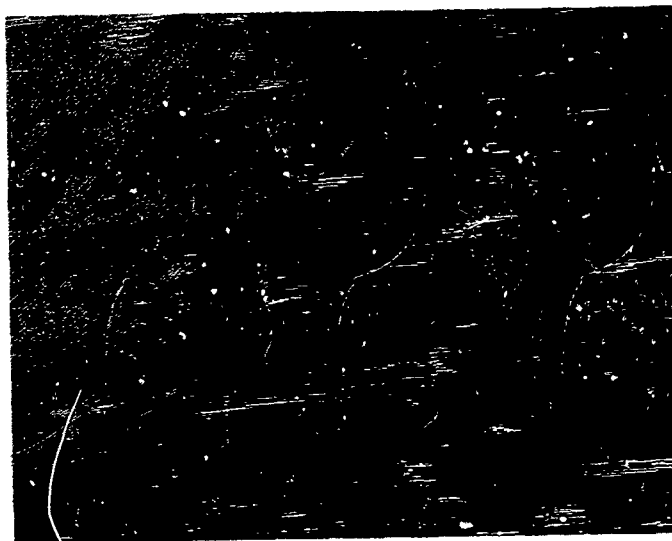
Vertical - 750 Psi/Major Division
Horizontal - 0.2 Sec/Major Division
Time Increasing To Left

Figure 59. Startup Characteristics - 8 and 10 GPM

80

characteristics of the Vickers Motorpump at various flow rates within the operating range of the unit.

The effect of the pressure feedback within the pump is illustrated by the damped oscillation of the rising pressure waveform at all flow rates below 10 GPM.

The time to reach maximum developed pressure is approximately 1.2 seconds and is relatively independent of any flow restriction.

2.4.5 Loaded Actuator Test

Fig. 60 through 62 show the temperature time history of the Vickers Motorpump device when the assembly was used to power the simulated aerodynamically loaded F-4 stabilator actuator.

The figures illustrate the large effect duty cycle has on the effective rate of temperature rise of the Vickers Motorpump and connected system. By comparing Fig. 61 with Fig. 52 it is evident that the rate of temperature rise for operating in the steady state blocked flow mode is comparable to that achieved at a cyclic rate of 0.5 H_z and $\pm$ 1 inch deflection.

By comparing Fig. 62 and 63 with Fig. 53 it is apparent that the rate of temperature increase at larger strokes of $\pm$ 2 and $\pm$ 2-1/4 inch deflection is considerably lower than that developed by continuous operation at 2 GPM or higher flow rates.

The selected cyclic rate of 0.5 H_z and the limited flow from the Vickers Motorpump resulted in a maximum stroke of $\pm$ 2.25 inches for this test series.
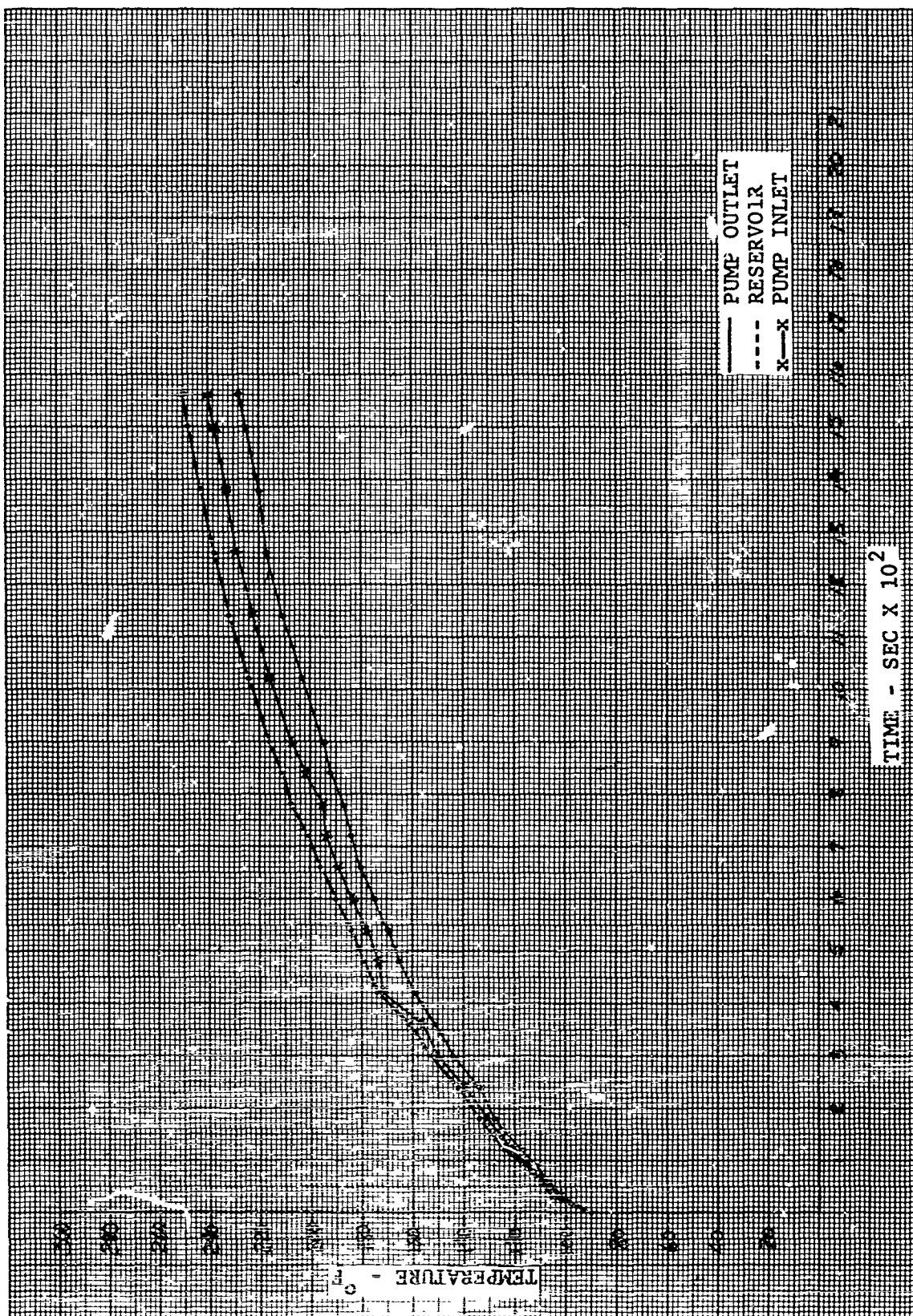
Figure 60. Temperature Time History - ± 1 Inch Deflection
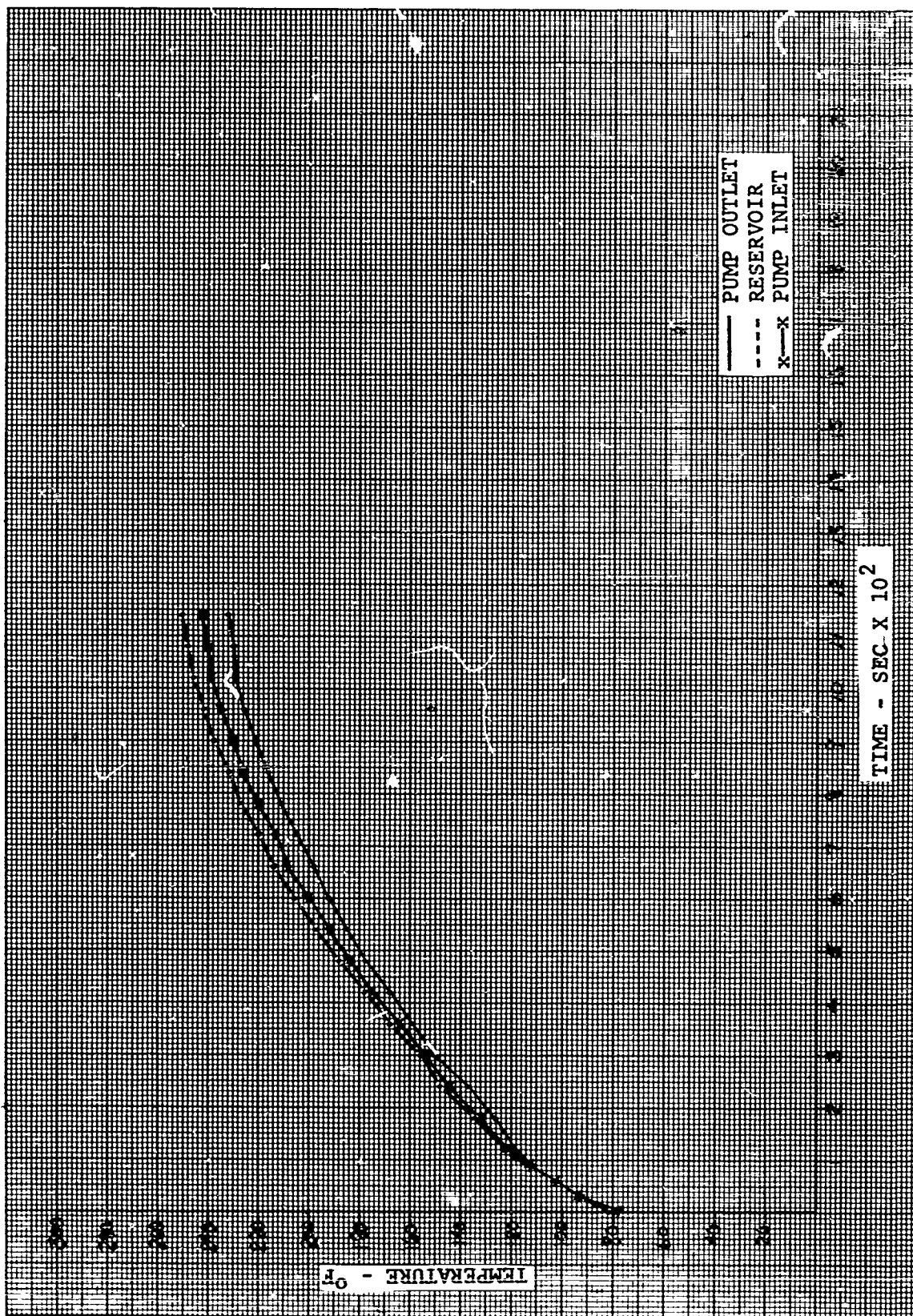
Figure 61. Temperature Time History - ± 2 Inch Deflection
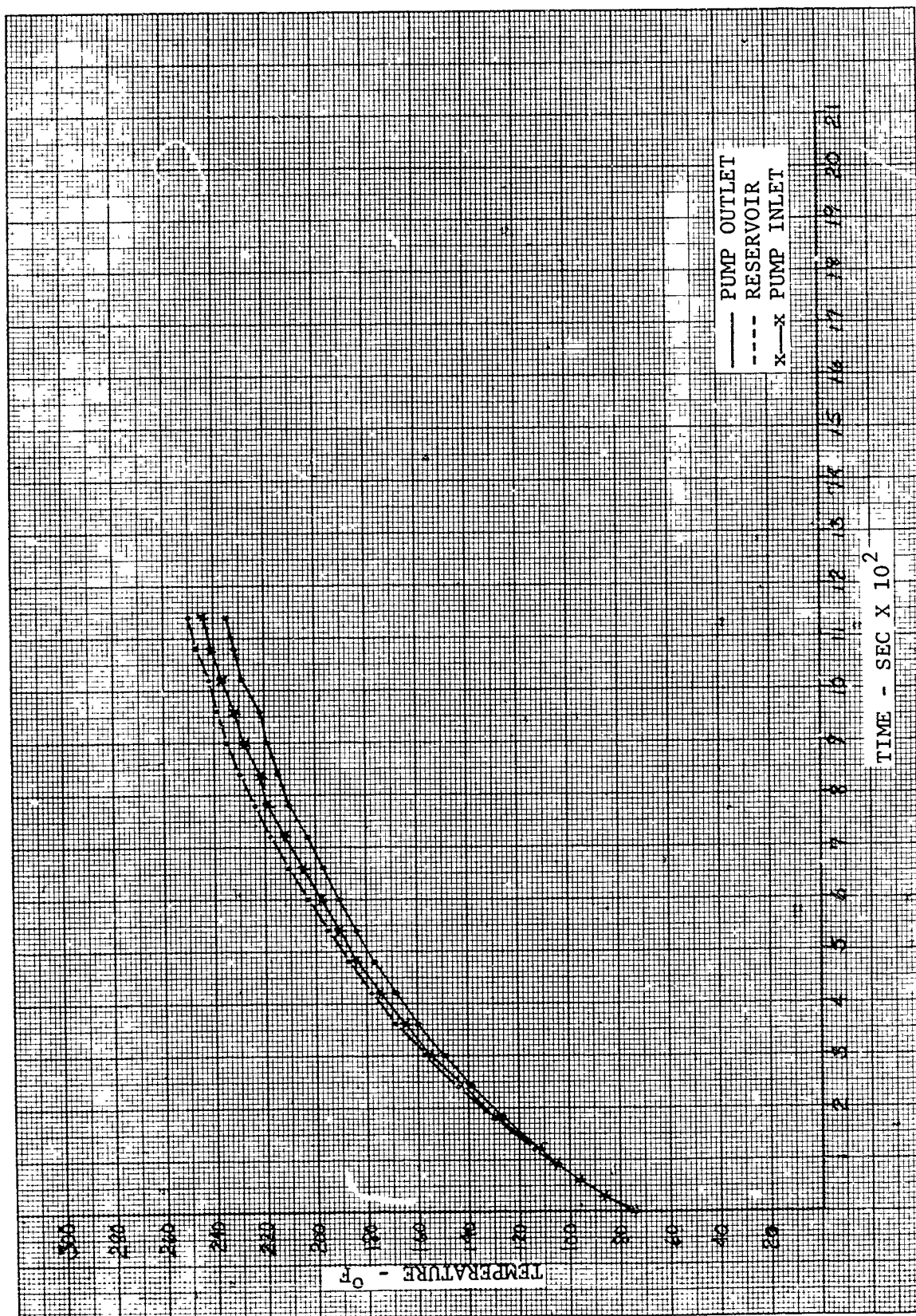
Figure 62. Temperature Time History - ± 2.25 Inch Deflection

84

2.5 Conclusions

2.5.1 The Vickers Motorpump is suitable as a potential emergency hydraulic power source for use in critical or sensitive portions of an aircraft flight control system.

2.5.2 The motor portion of the package will run under load with input voltages as low as 140 volts leg to neutral with very little heat buildup.

2.5.3 The Vickers Motorpump will not start if the input voltage is less than 180 volts leg to neutral and the steady state flow demand is less than 2.0 GPM.

2.5.4 The pressure compensation system within the Vickers Motorpump is effective in maintaining a reasonable constant pressure characteristic within the nominal operating range of 0 - 8 GPM. The pressure droop is characteristic of a differential cut off type pressure compensation mechanization.

2.5.5 The probable temperature rise characteristic of the Vickers Motorpump operating as an emergency hydraulic power source, lies between the blocked flow characteristic curve (level flight, little control input required) and the 2 GPM steady state flow condition.

2.5.6 The start up time of 1.2 seconds is sufficiently long that the effect of the delay on control loss should be evaluated in any application of the package as an emergency system.

2.6 Recommendations

2.6.1 The Vickers Motorpump should be modified to incorporate the manufacturers electrical pressure cut off to permit the device to start at very low line voltages with very little internal pressure buildup. This modification will permit the user to utilize the excellent reduced voltage operating tolerance of the device after start-up.

2.6.2 The system to which the Vickers Motorpump will be adapted should incorporate a properly sized accumulator to fulfill surge flow demands beyond the normal capability and response of the motorpump and limit the pressure surges

within the system.

2.6.3 To prevent a temporary control loss due to the start up time of the package, it is recommended that the pump be started before engagement as an emergency system is required. The package could be run with the pump output bypassed (giving the least heat buildup) and when required, be switched out of bypass using a high speed solenoid valve.

3. EVALUATION OF THE POLARIS INTEGRATED ACTUATOR PACKAGE

The Polaris actuator was manufactured by Hydraulic Research and Manufacturing Company, Valencia, California. Lockheed Aerospace Company, Burbank, California, used the actuator to provide the necessary control forces to steer a Polaris missile during the ascent portion of the flight envelope. The required operating life of the device was less than 20 minutes.

3.1 Device Description

The Polaris integrated package actuator is shown in Fig. 63. Hydraulic power is developed by a fixed displacement piston pump which is driven by a totally enclosed 28 volt, 2 HP DC motor. A flapper nozzle servovalve with a maximum flow gain of 0.92 GPM @ 3000 psi and 18 ma controls the flow to the actuator portion of the assembly in response to drive signals from an external servoamplifier. The actuator has an effective area of 0.99 in^2 which results in a maximum slew rate of 3.54 in/sec.

Position feedback from the actuator is provided by an internal LVDT assembly which has an open circuit output of 4 volts/inch with 24 volt, 400 H_z excitation. The piston pump, actuator and feedback transducer are assembled within a cast aluminum housing. The housing also contains (1) a reservoir volume, which is pressurized by a bootstrap piston coupled to the pressure output from the pumps, (2) a return pressure relief valve, (3) a high pressure cut-off switch, (4) a reservoir fluid level switch to prevent operation of the device if the reservoir volume is not within limits, and (5) a metering rod to indicate the level of fluid contained in the bootstrap reservoir.

3.2 Test Purpose

The Polaris integrated package actuator performance capability must by nature of the design be dependent on the integral quality of the DC power source. Furthermore, the high density high energy packaging technique, represented by the Polaris actuator and typical of most limited life fluid media integrated actuator designs, tends to reduce the operational life of the mechanization. This is caused by breakdown of the limited quantity of working
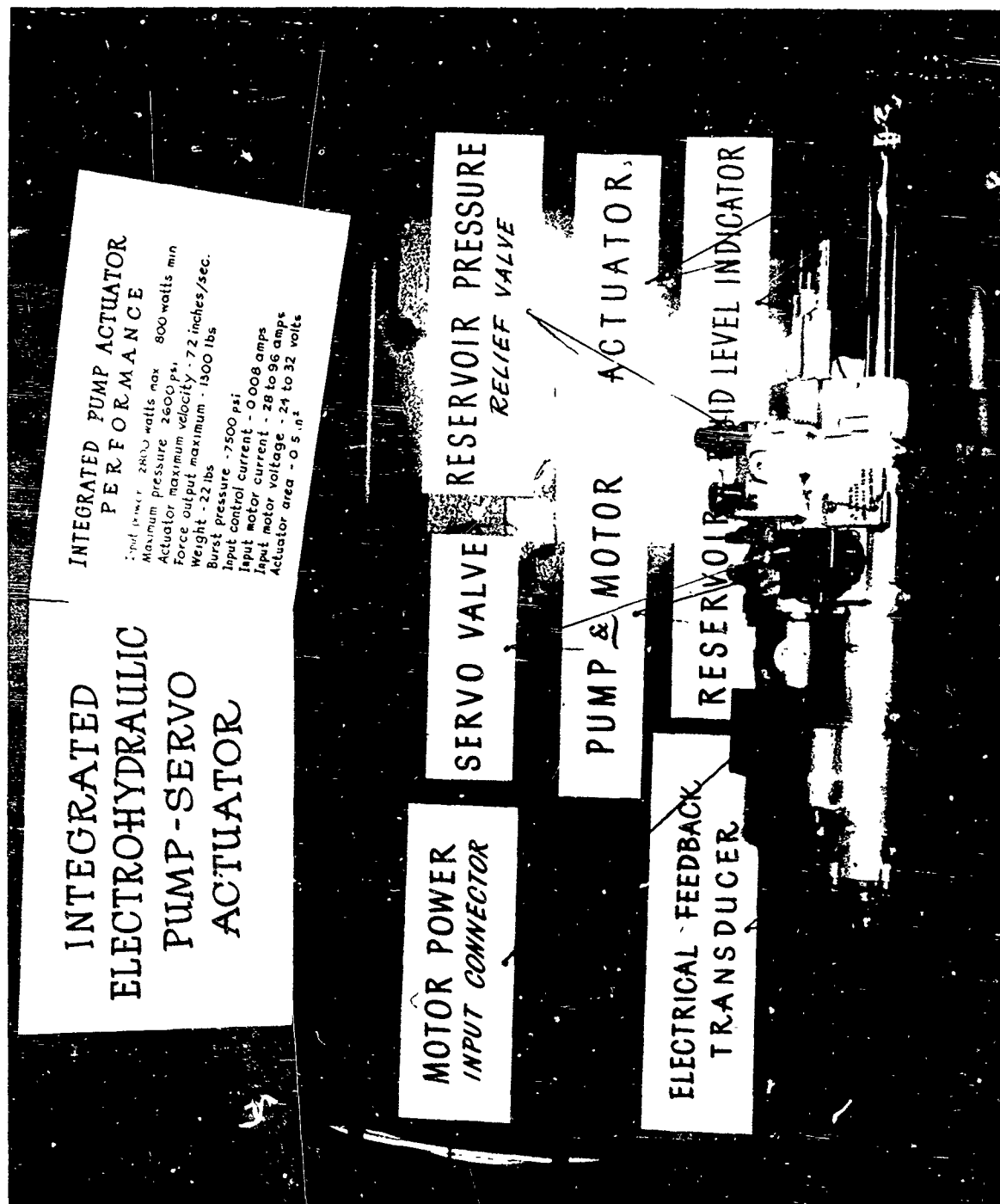
Figure 63. Polaris Integrated Actuator

fluid, failure of static and dynamic seals due to high temperature operation, and deterioration of internal electrical assemblies such as torque motors, solenoids, and displacement transducers as a result of their proximity to or assembly within the hot actuator body.

The Polaris test schedule was developed to evaluate the design integrity and useful life of the pump, servovalve motor, seals, etc. under conditions more typical of an application of the Polaris device than to a fly-by-wire flight control system for a manned aircraft. Therefore, the purpose of the Polaris test series is:

    1. Determine the change in the nominal performance characteristics of the actuator when the DC supply voltage is increased or decreased.

    2. Determine the effects of prolonged operation of the actuator under continuous cyclic conditions.

3.3 Test Stand Description

The Polaris integrated package actuator was connected to the test stand shown diagrammatically in Fig. 64. The 28 volt DC source was monitored with voltage and current meters. Voltage drop in the DC supply to the motor was minimized by the use of a galvanometer type current meter and meter shunt.

Due to the prolonged test schedule, it was necessary to connect an external hydraulic source to the Polaris actuator to circulate cooled hydraulic fluid through the Polaris actuator pressure connection upstream of the bootstrap reservoir. The circulating fluid was then returned to the external hydraulic source via a fitting inserted in place of the low pressure relief valve. This recirculating fluid loop continuously bypassed a portion of the working fluid through an external heat exchanger. The actuator body temperature was maintained at 110°C (limited by hydraulic fluid characteristics) by adjusting the flow control valve inserted in series with the actuator. The status of the recirculating cooling loop was monitored with a low pressure gage and flowmeter.
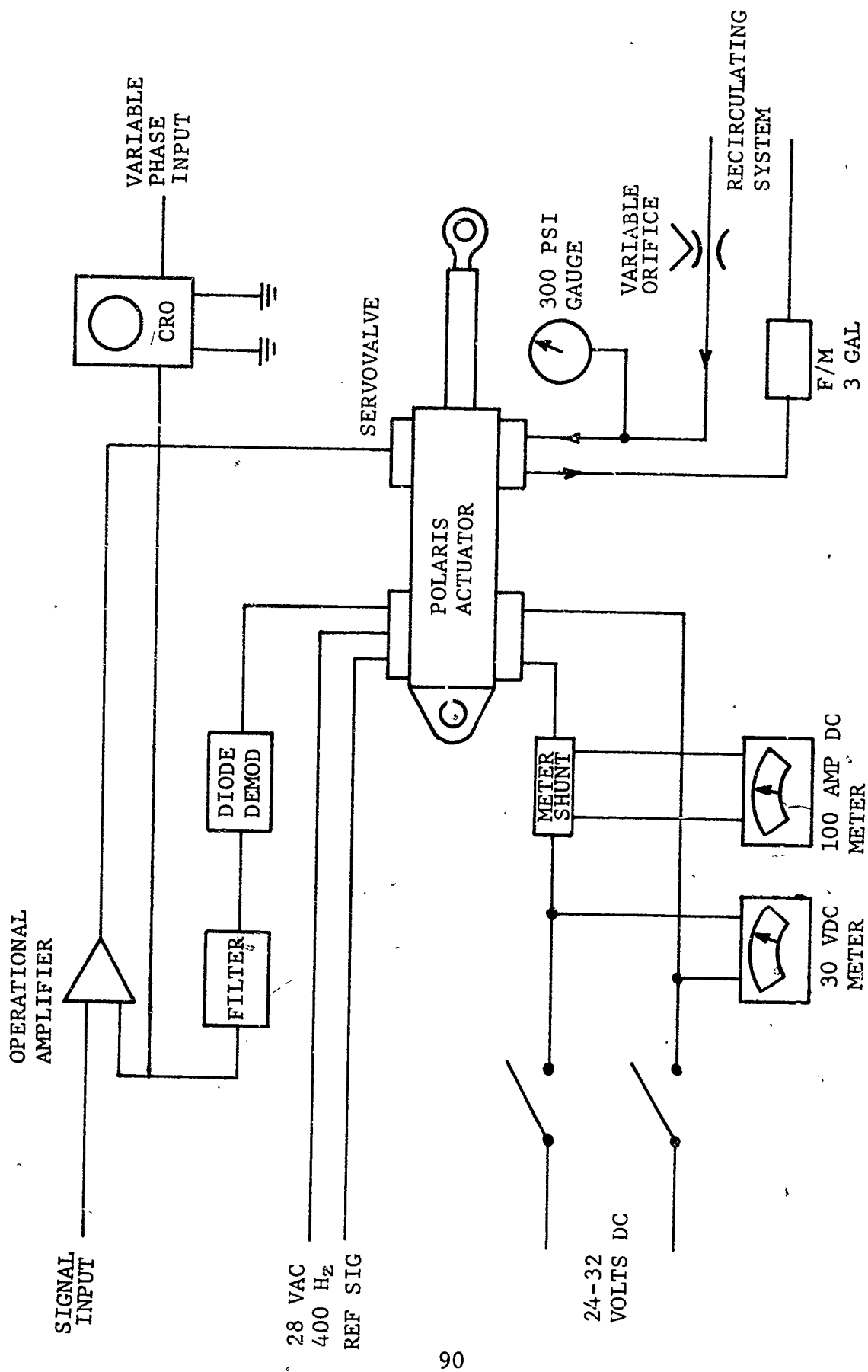
Figure 64. Polaris Test Stand Schematic Diagram

90

The internal linear variable differential transformer was excited from a 24 volt RMS, 400 H_z single phase supply. The transducer output (4 volts/inch open circuit) was demodulated with a "Collins" diode ring demodulator and filtered with the second order time lag network. The filter was designed to have a -3 db break point at 30 H_z; an order of magnitude above the calculated frequency response of the closed loop servo system assembled to drive the Polaris actuator. The complete Polaris test stand is shown in Fig. 65.

The transducer gain after demodulation and filtering (2.85 volts/inch) and the known flow gain of the Polaris servovalve were used to calculate the servoamplifier gain required to provide a closed loop servo response of 3 H_z at the -3 db break point.

3.4   Test Schedule Description

3.4.1   <u>Dynamic Response vs. Applied Voltage</u>

The Polaris test stand servoamplifier was driven with a sinisodial input from a function generator. The function generator provided a second output identical to that applied as an input signal with the exception that the phase of this signal could be adjusted to lead or lag the input signal to the Polaris test stand. The amount of phase lead or lag could be read directly from a calibrated dial. The frequency of the input signal was swept from 0.1 H_z to 10.0 H_z. The amplitude of the input signal was established at a level below that which would cause saturation in the servoamplifier or servovalve at 0.1 H_z.

The Polaris integrated package actuator amplitude degradation relative to a zero db point of 0.1 H_z was determined by monitoring the displacement transducer feedback signal at the output of the filter network.

The phase shift characteristics of the Polaris servo-actuator system was readily established by adjusting the function generator phase shifted output to obtain a Lissajous pattern on an oscilloscope which was indicative of zero relative phase shift. The actual phase shift at a given frequency was then read directly off the calibrated dial on the function generator.

The dynamic response of the Polaris integrated actuator
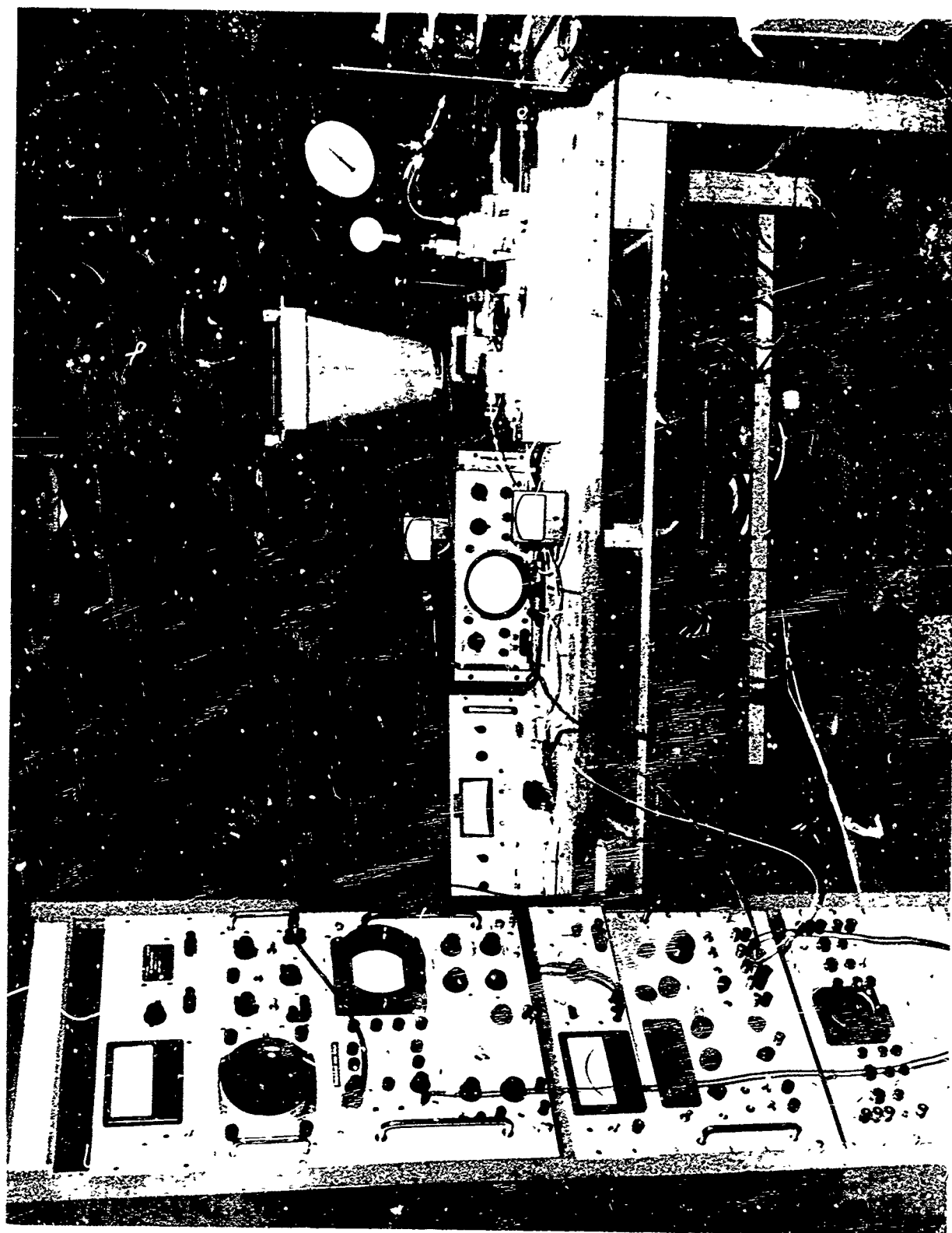
Figure 65. Polaris Test Stand

was initially evaluated at nominal input conditions of
27 volts DC. The test was repeated for applied voltages
of 22 and 32 volts DC.

3.4.2 Dynamic Life Test

The Polaris integrated package actuator was operated
with a 3 H_z sinusoidal input signal and nominal applied
voltage. The amplitude of the input signal was adjusted
to the maximum possible level that would not cause satura-
tion effects. The DC motor operating conditions (voltage
and current), the actuator body temperature, and the ac-
crued operating time were monitored and recorded through-
out the test.

The Polaris integrated actuator was run continuously
on a day to day basis. The dynamic response of the actua-
tor was reevaluated weekly and the test was continued until
the actuator incurred a complete failure.

3.5 Test Results

The operation of the Polaris actuator became erratic
during the initial evaluation of the nominal dynamic res-
ponse characteristics. The problem was diagnosed as ran-
dom speed variations of the DC motor. An inspection of
the motor indicated that the soldered electrical contacts
had broken as a result of the heat buildup in the totally
enclosed electric motor.

The motor had been operated for at least 85 minutes
before the problem occurred, whereas the required opera-
ting life for the actuator for the Polaris missile appli-
cation is only 17 minutes.

The connections were resoldered and the motor cover
was trimmed and shaped to permit attachment of an external
blower and duct work to direct a large flow of air through
the motor enclosure.

3.5.1 Dynamic Response vs. Applied Voltage

Fig. 66 is a plot of the dynamic response of the
Polaris integrated actuator under nominal power input
conditions. The dynamic response referred to the -3db
break point was 3.5 H_z with a servoamplifier gain of 9.5
ma/volt. The actuator deflection was ± 0.33 inches at

93
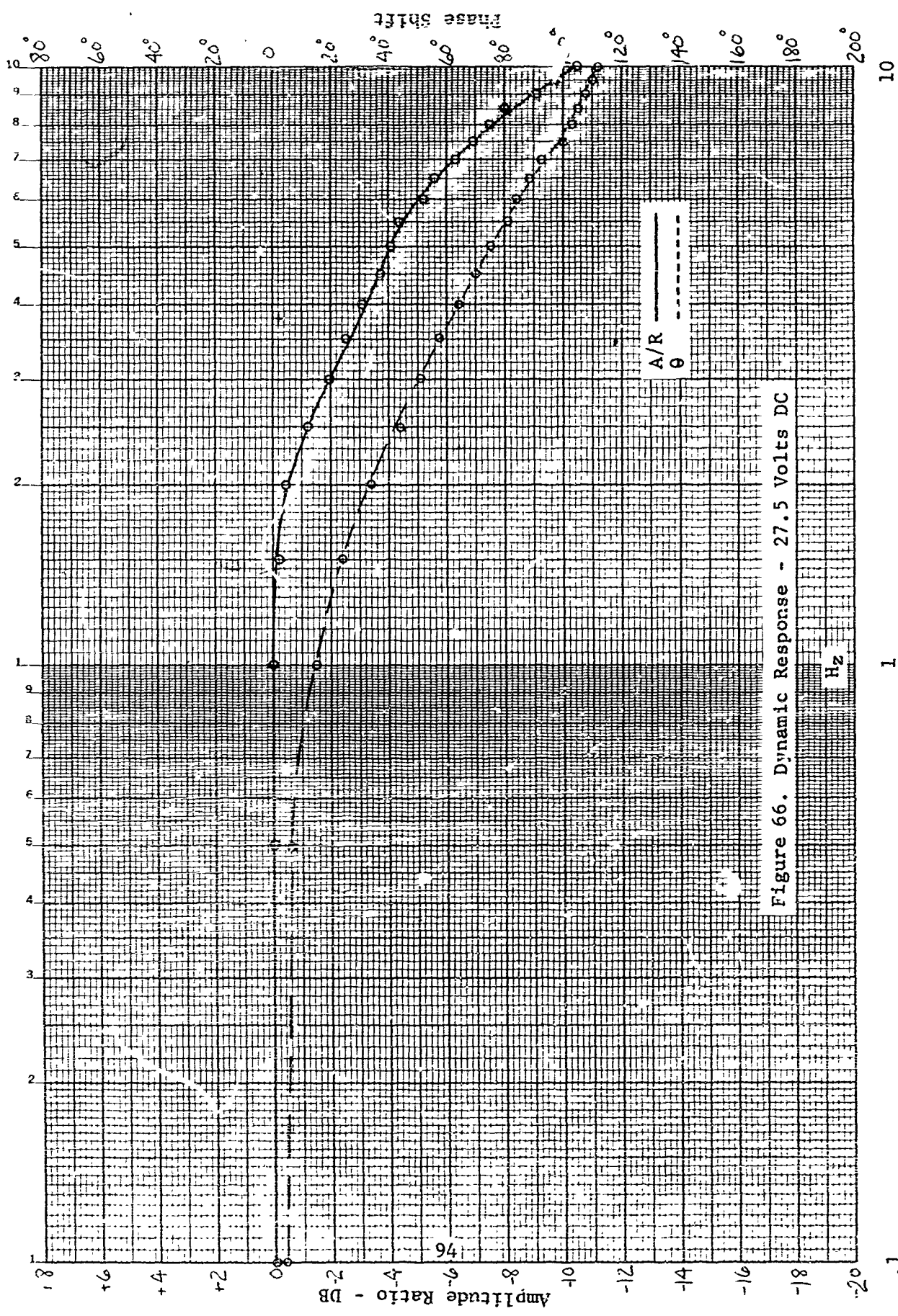
Figure 66. Dynamic Response - 27.5 Volts DC

94

3 H_z.

Fig. 67 shows that the dynamic response characteristics did not change when the applied voltage was increased to 32 volts. However, Fig. 68 shows that the dynamic response decreased to 2.5 H_z at the -3 db point when the applied DC voltage was reduced to 22 volts. This degradation was accomplished by saturation effects which made it necessary to reduce the amplitude of the driving signal.

This characteristic is to be expected. The speed of the DC motor is proportional to the applied voltage. Thus a reduction in the applied voltage will cause a reduction in the flow of hydraulic fluid from the internal pump and a corresponding drop in the linear velocity limit of the servovalve. The input signal was previously established just below saturation level. Therefore, the actuator motion will now be nonlinear, as indicated by the distorted (saturated) waveform observed at the LVDT filter output terminals when the voltage applied to the driving motor was reduced to 22 VDC.

3.5.2 Dynamic Life Test

The Polaris integrated package actuator operated continuously for 213 hours without any significant change in the performance characteristics. Total failure occured at this time as a result of the complete consumption of the carbon brushes in the motor. There was no indication of any abnormal seal leakage, wear or power input fluctuations during the period of the test.
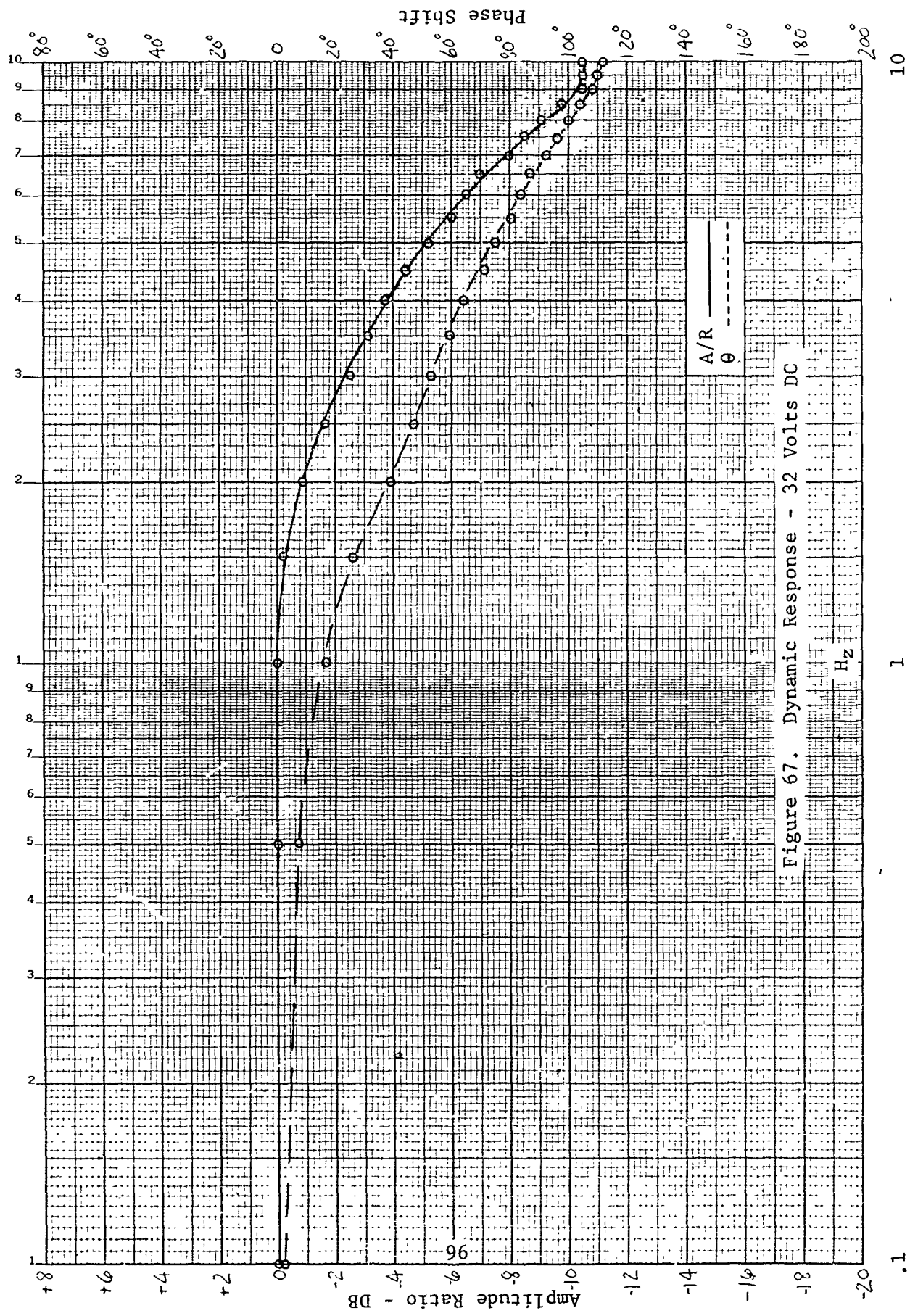
Figure 67. Dynamic Response - 32 Volts DC
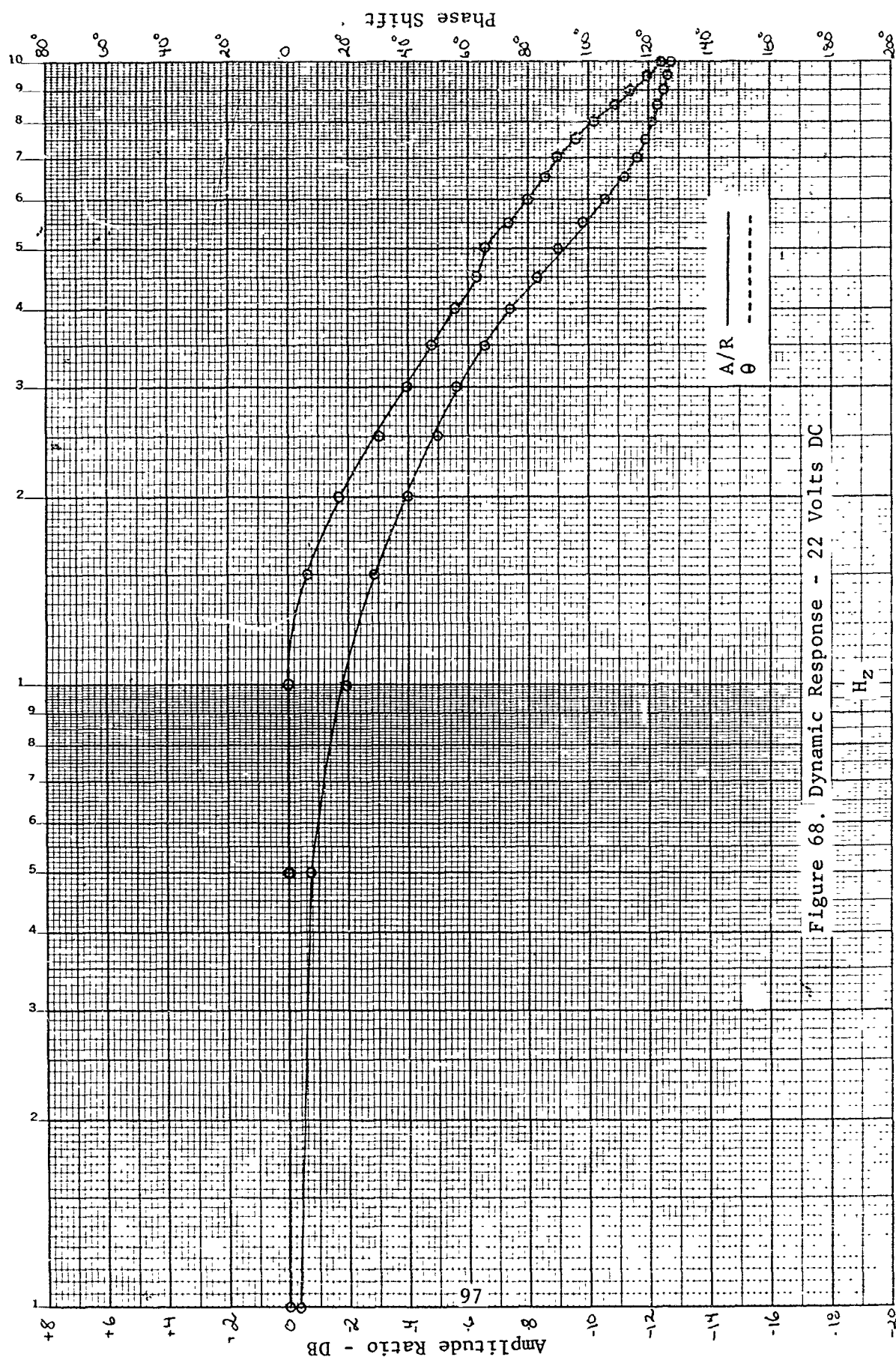
Figure 68. Dynamic Response - 22 Volts DC

97

3.6 Conclusions

3.6.1 The DC driving motor of the Polaris integrated
actuator will operate effectively over an applied vol-
tage range of 24-32 volts DC with no significant change
in the performance characteristics of the Polaris ac-
tuator. The service life of the mechanism is limited
by the pump motor design and construction; however, the
actual service life is very conservative in consideration
of the 17 minute operating life specification.

3.6.2 With the exception of the DC motor, the component
hardware packaged within the Polaris actuator assembly
demonstrates the anticipated conservative life expectancy
typical of servohydraulic hardware.

3.7 Recommendations

The following recommendations are offered in consi-
deration of the modifications that would be required to
use the Polaris actuator for aircraft fly-by-wire flight
control systems.

3.7.1 The Polaris integrated actuator pump motor should
be changed to a 400 H_z sychronous design to eliminate a
large majority of the heat generated by the internal resis-
tance losses typical of a low voltage high current DC motor.
An additional and very important benefit as a result of
this recommended change will be to substantially increase
the service life of the entire assembly.

3.7.2 The Polaris integrated actuator should be equipped
with a forced convection head exchanger to dissipate the
energy imparted to the hydraulic fluid at a rate sufficient
to result in a stabilized actuator body temperature of
250°F. The blower for the heat exchanger should be driven
from the same prime mover that powers the hydraulic pump.

3.7.3 The modified Polaris actuator should be requalified
for flight test evaluation.

4. EVALUATION OF THE McDONNELL DOUGLAS FBW SYSTEM

The McDonnell Douglas FBW system (Ref. 3) was designed as a laboratory model demonstrator of a single axis redundant fly-by-wire flight control system.

The objective of the McDonnell Douglas FBW program was to design, fabricate, and evaluate a fly-by-wire flight control system compatible with the flight control requirements of aircraft of advanced design. An additional requirement was that the system offer a potential for significant improvement in reliability over currently proposed electrical flight control systems.

The McDonnell Douglas FBW system evaluated in this section of this report was developed under USAF Contract AF33 (615)-8958, under the direction of the Flight Dynamics Laboratory, WPAFB, Dayton, Ohio. The effort was completed in July 1968.

4.1 General System Description

The McDonnell Douglas triple redundant FBW flight control system is an electrohydraulic single fail operate, median select mechanization which controls the position of an actuator in response to flight control commands originating at a pilot's control stick. The system evaluated and reported in this section of this report is shown in simplified form in the schematic diagram of Fig. 69. The principal parts of the system are: an electrohydraulic servoactuator which can accept three electrical signal inputs, three channels of electronic demodulators and servoamplifiers and four sets of LVDT triple tandem position transducers.

System operating and monitoring is provided by a switch matrix and instrumentation installed in a control console shown in Fig. 70. The console also houses the channel electronic mocules and a patchboard where all system interface connections were made.

In addition, the servoactuator, pilot control stick and feel system, and a moveable surface and actuator load system were mounted in a large test bed frame shown in Fig. 71.

99
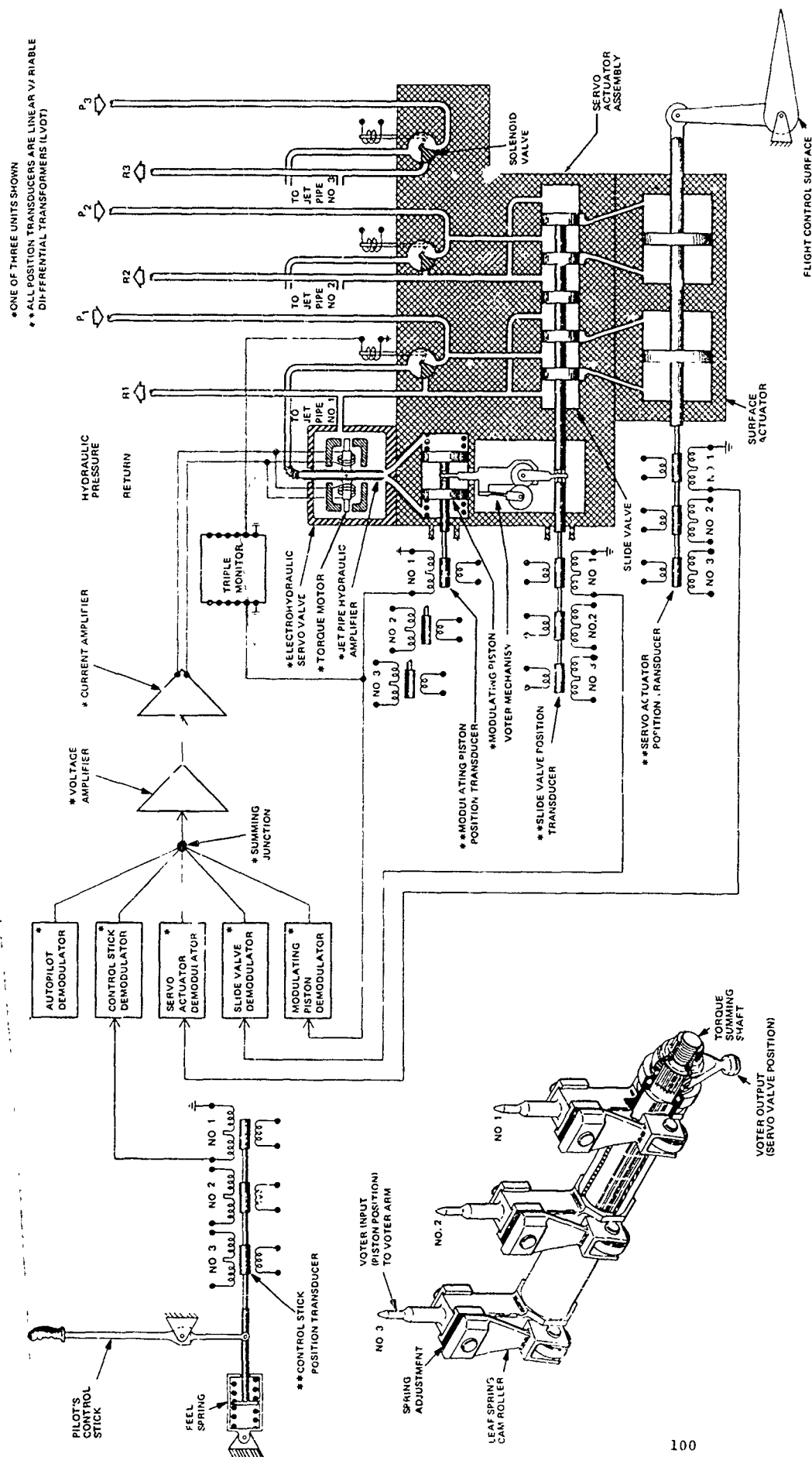
Figure 69. McDonnell Douglas FBW System Schematic Diagram

Figure 70. Control Console

101
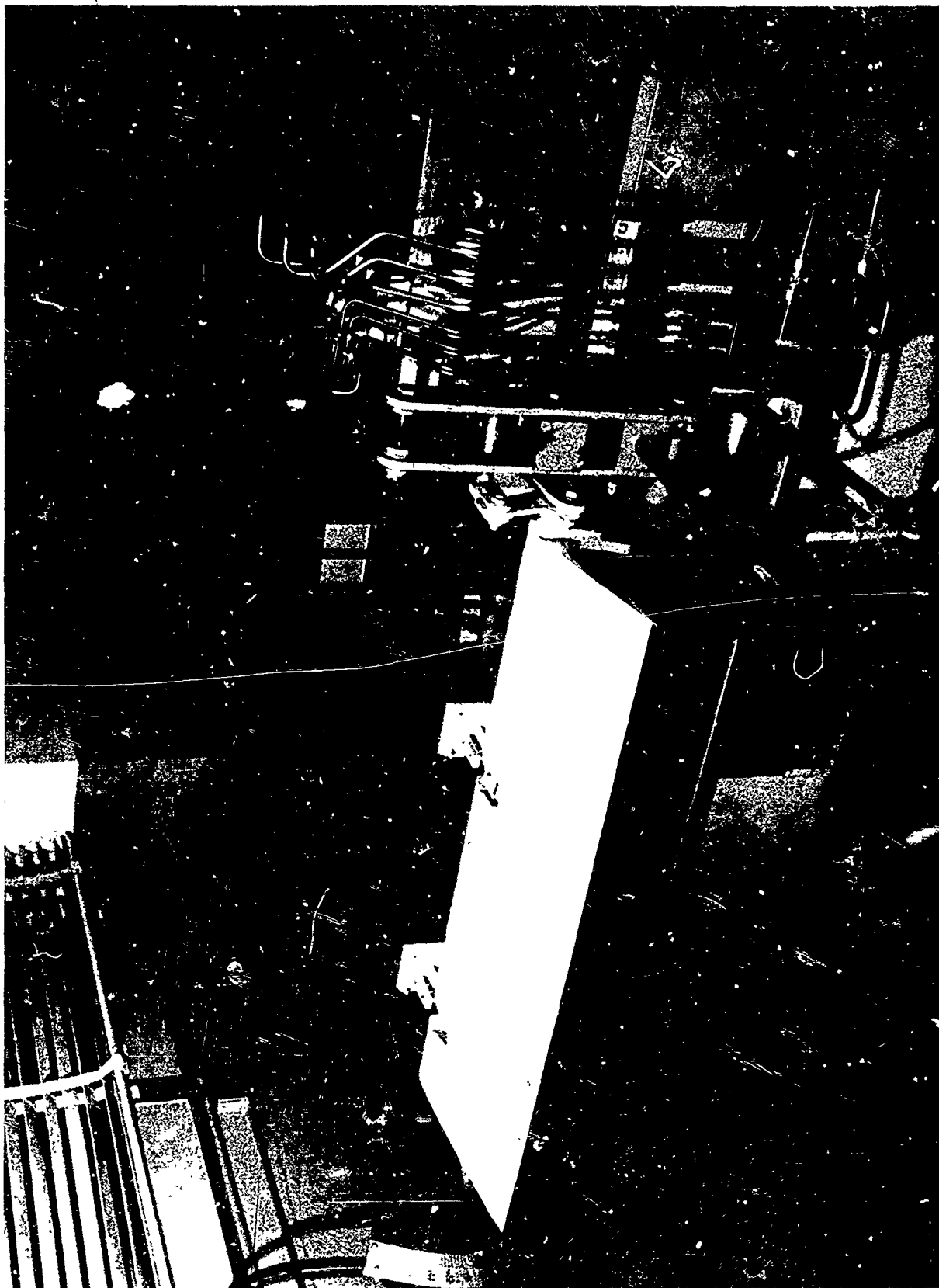
Figure 71. Test Bed Frame

4.2 Mechanization Description

4.2.1 Pilot's Control Stick

Control inputs are applied to the pilot's control stick. The movement of the control stick is restricted by a spring and rate damper to simulate the "feel" characteristic of a small fighter aircraft.

The movement of the lower end of the control stick is converted into three identical electrical signals by a triple tandem LVDT position transducer attached between the control stick and the base of the mounting platform. The output of the LVDT is a 400 H_z waveform varying in amplitude and polarity in response to pilot inputs.

4.2.2 Control Channel Electronics

The McDonnell Douglas FBW system contains three identical control channel electronic modules. Each module contains five synchronous demodulators, a voltage amplifier and summer and a servovalve drive or current amplifier. In addition, each module also contains the DC supplies for the servoamplifiers and the excitation source for the LVDT assemblies.

The three electrical signals developed by the control stick LVDT assembly are synchronously demodulated by a "chopper" driven from LVDT excitation source. The "chopper" output is an 800 H_z full wave demodulated waveform that varies in amplitude and polarity in response to pilot control inputs.

The demodulated control stick signal and the negative feedback signals from the servoactuator are summed algebraically at the input to the channel electronic voltage amplifiers. The resulting error signal is amplified and converted to a current output in the valve drive or current amplifiers. Therefore, the channel electronics output is three very nearly identical current drive signals proportional to the difference between the commanded position of the hydraulic actuator and the actual position achieved.

4.2.3 Servovalve

The current signals from the control channel elec-
tronics are applied to three separate jet pipe servovalves.
The current drive results in a displacement of the arma-
tures of the torque motors and attached jet pipe which
creates a differential pressure across the discharge ports
of the servovalve. The differential pressure is propor-
tional to the current input to the servovalve.

The flow of pressurized hydraulic fluid to the servo-
valve is controlled by a solenoid actuated shut off valve.
When activated, the shut off valves block the flow of hy-
draulic fluid to the servovalve and bypasses the servo-
valve jet pipe.

4.2.4 Modulating Piston

The differential pressure output of each of the three
jet pipe servovalves is directed to one of three "modula-
ting" pistons. Each modulating piston assumes a position
where the force generated by the differential pressure ap-
plied to the effective area of the piston is just balanced
by the resisting force of the centering springs and coupled
loads.

The position of each modulating piston is sensed by
an LVDT assembly. The LVDT electrical signal is fed back
to the respective channel electronic module where it is
demodulated and subtracted from the control stick input
to form the inner loop of the servomechanism.

4.2.5 Voter Mechanism

The movement of each modulating piston is coupled
to one arm of the unique "voter" mechanism shown in Fig.
72. This device mechanically selects one of the three
driving channels and transmits the selected channel modu-
lating piston movement to the hydraulic actuator control
valve.

The voter arms that couple the modulating piston to
the voter output shaft carry along a cantilever spring
loaded roller cam which engages a machined groove in the
voter mechanism output shaft. The rollers are preloaded
into the groove and exhibit a detent characteristic for

104
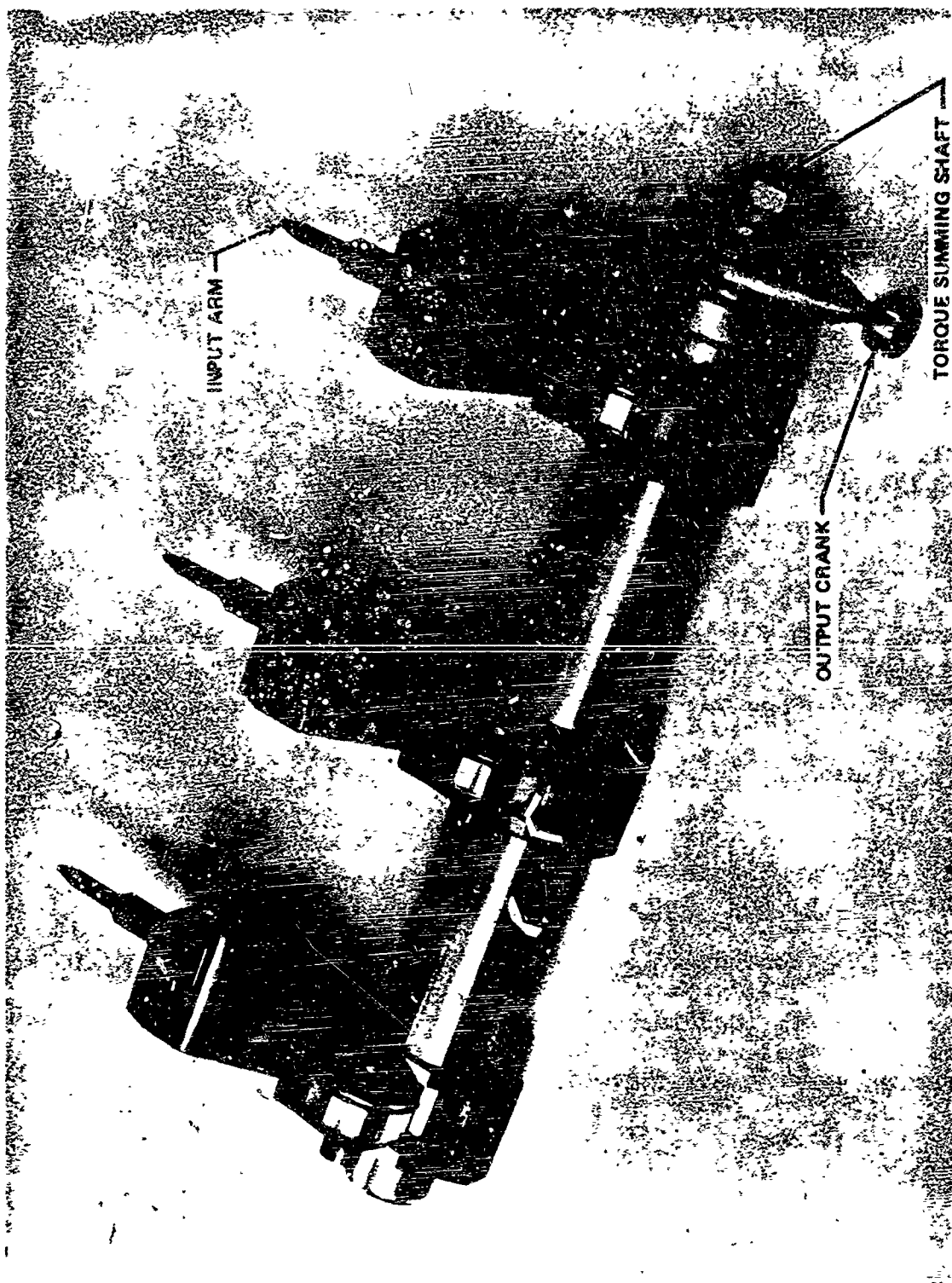
Figure 72. Voter Mechanism

INPUT ARM

TORQUE SUMMING SHAFT

OUTPUT CRANK

105

very small angular deflections of the voter arms as shown in Fig. 73. Angular deflections greater than .01 radians cause the roller to break out of the cam groove.

The voter arm torque input to cause voter arm movement must exceed the threshold or breakout value defined by the geometry of the cam groove and the preload force of the voter arm cantilever spring. Furthermore, the cam geometry limits the torque applied to the voter output shaft by any one voter arm to a value equal to the breakout torque and effectively maintains this torque level throughout the nominal range of angular movement of the voter arm.

Normal interchannel tracking errors between the three identical control channels and the effects of the system dynamic characteristics will result in a random and continually changing distribution of the voter arm rollers about the center of the cam groove. The voter output shaft will continuously follow the movements of the voter input arms and will always assume a position of torque equilibrium for which the summation of torques applied by the voter arms and reflected loads is equal to zero.

The voter mechanism output shaft will follow the movement of the median positioned voter arms. The voter arms that are not perfectly synchronized and detented in the cam groove will be positioned on either side of the cam groove such that their respective torque inputs are equal in magnitude but opposite in direction and self-cancelling.

The control of the position of the voter output shaft will continually pass from one channel to another as the voter system (modulating pistons, voter arms, voter output shaft and actuator slide valve) responds to the dynamic characteristics of the mechanization.

The reader is referred to the detailed description of this unique median select mechanization in reference 1.

4.2.6 Slide Valve

The voter mechanism output shaft movement is coupled
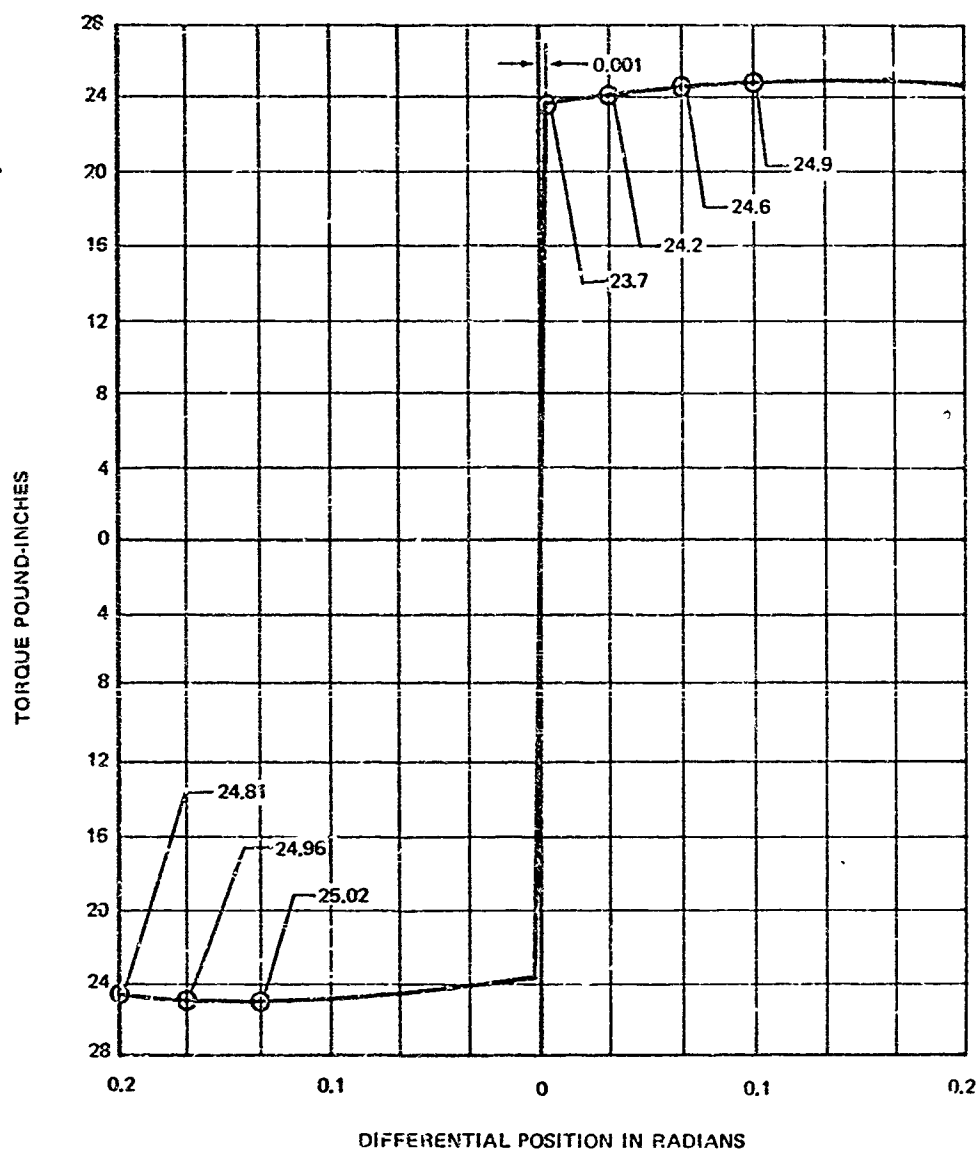
Figure 73. Voter Mechanism Detent Characteristic

107

to a dual tandem coaxial four way slide valve which meters the flow of hydraulic fluid to the actuator from two separate sources.

The slide valve is a two spool staged design. The voter mechanism output shaft engages a primary inner spool which is free floating (not spring centered). The outer spool is positioned to a neutral position within the valve housing by a set of centering springs. The inner spool picks up the outer spool midway through the total stroke of the slide valve and the two spools are driven in unison. The unique valve feature prevents blocking of the actuator motion due to valve jamming. Fig. 74 shows the assembled control valve.

4.2.7 Control Surface Actuator

The control surface actuator is a dual tandem hydraulic cylinder. The nominal operating pressure is 3000 psi. The effective area of each cylinder is 1.065 in.^{2} and the stroke is 3.300 inches. The hydraulic actuator also houses a triple tandem LVDT position transducer which generates an electrical signal analogous to the position of the hydraulic actuator.

The output of each of the three actuator LVDT assemblies is fed back to the respective channel electronic module where it is demodulated and subtracted from the pilot input at the summing junction of the voltage amplifier, thus forming the main or outer feedback loop of the servomechanism.

4.2.8 Test Bed

The servoactuator and load system of the Douglas FBW system are mounted to a large stable test bed shown in Fig. 75. A hinged surface creates the effect of an elevator so the operator can sense the effectiveness of the control system. The surface and the hydraulic actuator are coupled to one end of a torsion bar with a linkage system. The torsion bar was designed to resist the actuator motion with a hinge moment equivalent to an air-load appropriate for the size of the hydraulic actuator employed.
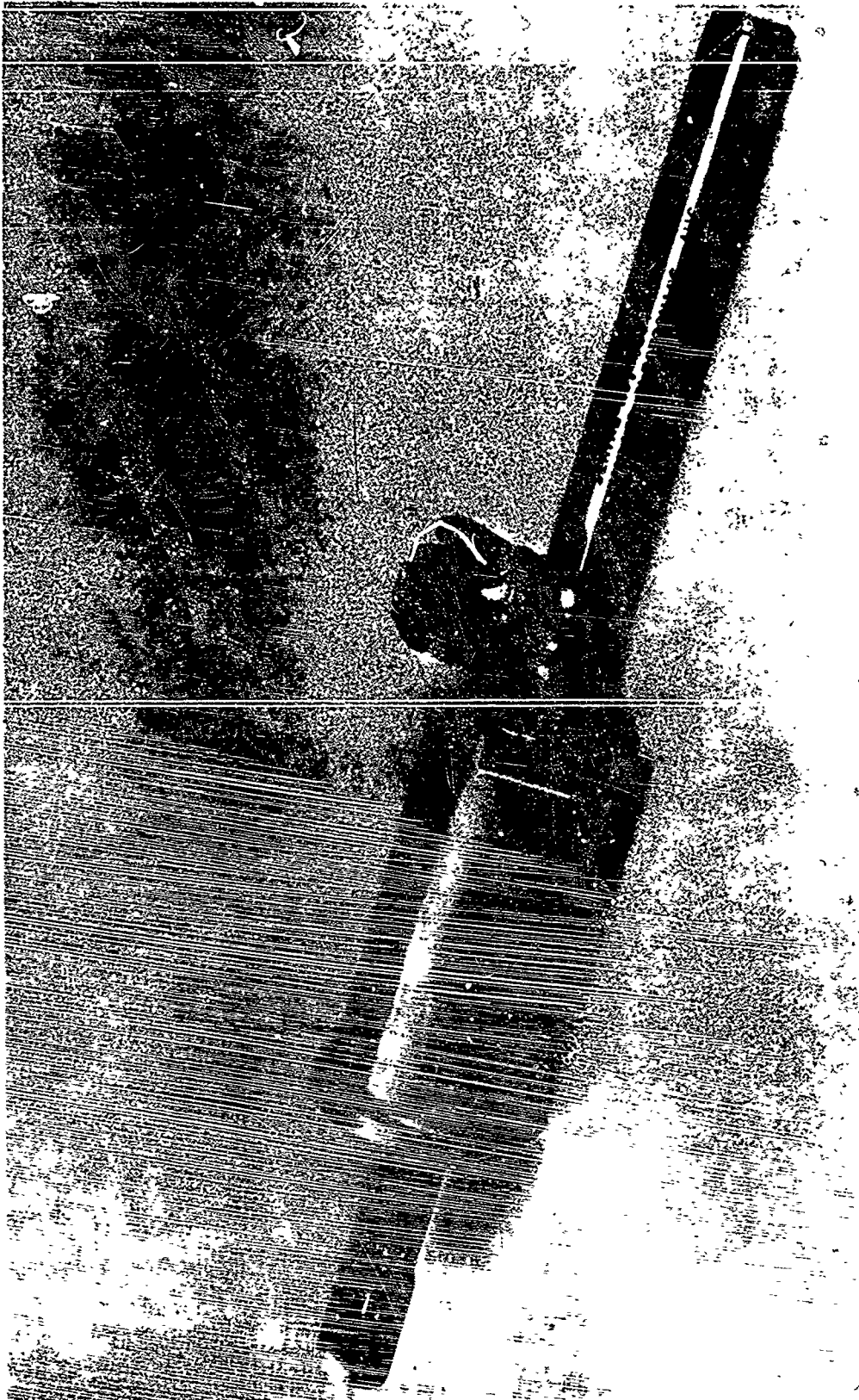
Figure 74. Assembled Control Valve
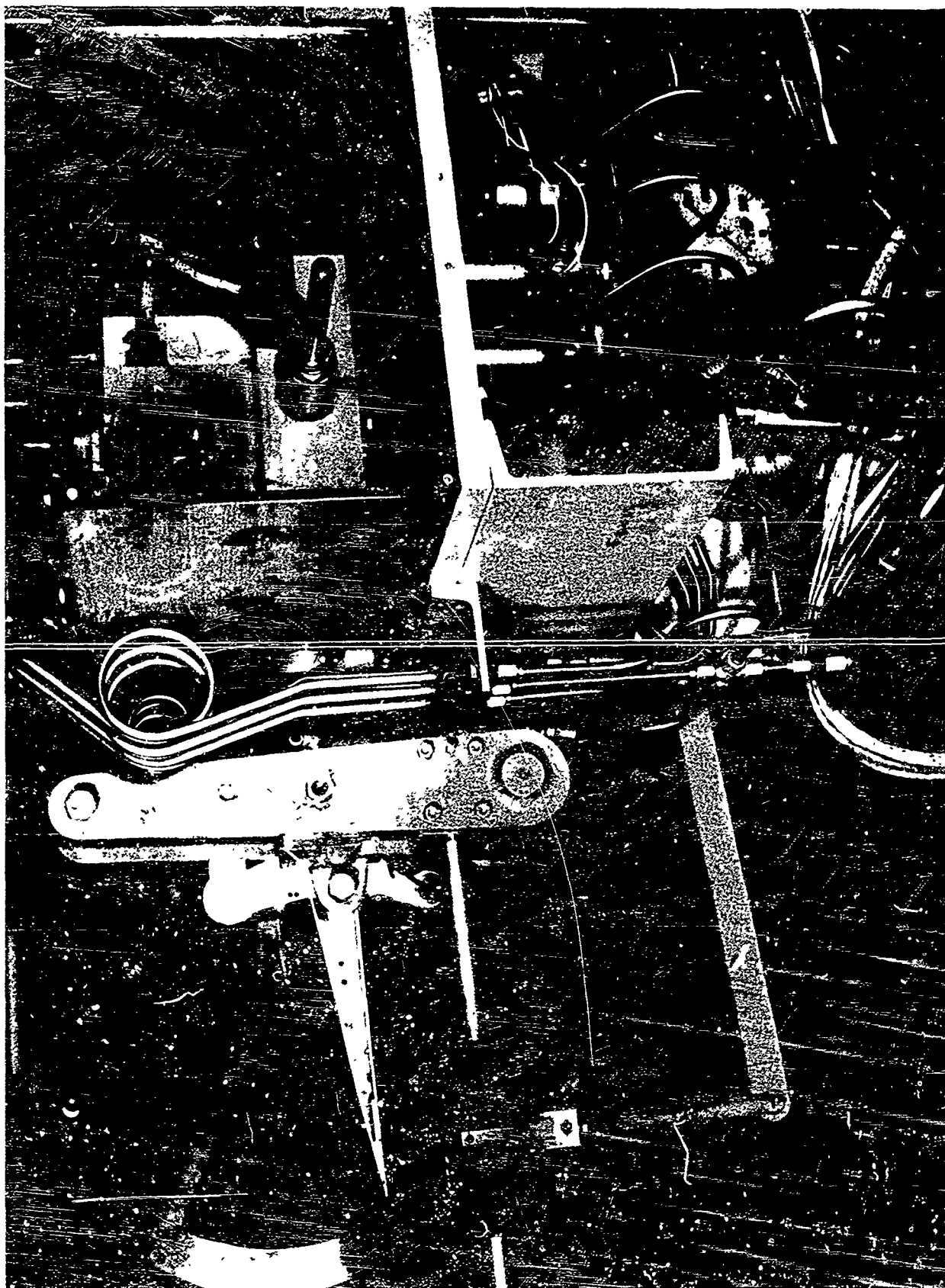
Figure 75. Servoactuator and Load Test System

110

The actuator load system was fitted with an additional inertia load and a damper to adjust the natural frequency of the attached load to a point where motion amplification due to structural resonance would not occur. Furthermore, a protractor assembly was attached to the test bed frame to visually indicate the angular deflection of the attached control surface.

The test bed also mounts: the pilot's seat, control stick, and torsion bar artificial feed system; the solenoid valves and attached plumbing to generate three controllable hydraulic sources from one laboratory pump stand and a junction box for termination and interconnecting of the electrical components remote from the test control panel.

4.2.9 Test Control Panel

The operation of the McDonnell Douglas FBW system is directed through the test control panel shown in Fig. 76. The test control panel provides the switch matrix, control circuitry and monitoring instrumentation for the control of the 115 volt 400 H_z and 28 VDC power sources for the complete system. Failure injection circuitry, control channel disconnects, hardover signal sources and hydraulic source control functions are available on the control panel. Status indicator lamps are provided as required. Storage space is provided for the three control channel electronic modules and a spare unit.

4.3 Control Channel Failure Detection

The quality of the three individual control channels is continually evaluated by an electronic monitor shown in Fig. 77. The monitor works in conjunction with the servoactuator assembly and functions in the following manner.

Three independent modulating piston LVDT output signals are available from the servoactuator assembly. In normal operation these signals track within close tolerances and supply virtually identical inputs to the monitor. In the event of a failure, one of these signal inputs will differ from the other two. The function of the monitor is to constantly compare all three signal inputs and detect a significant (20%) variation of one from the other

111

Figure 7b. Test Control Console
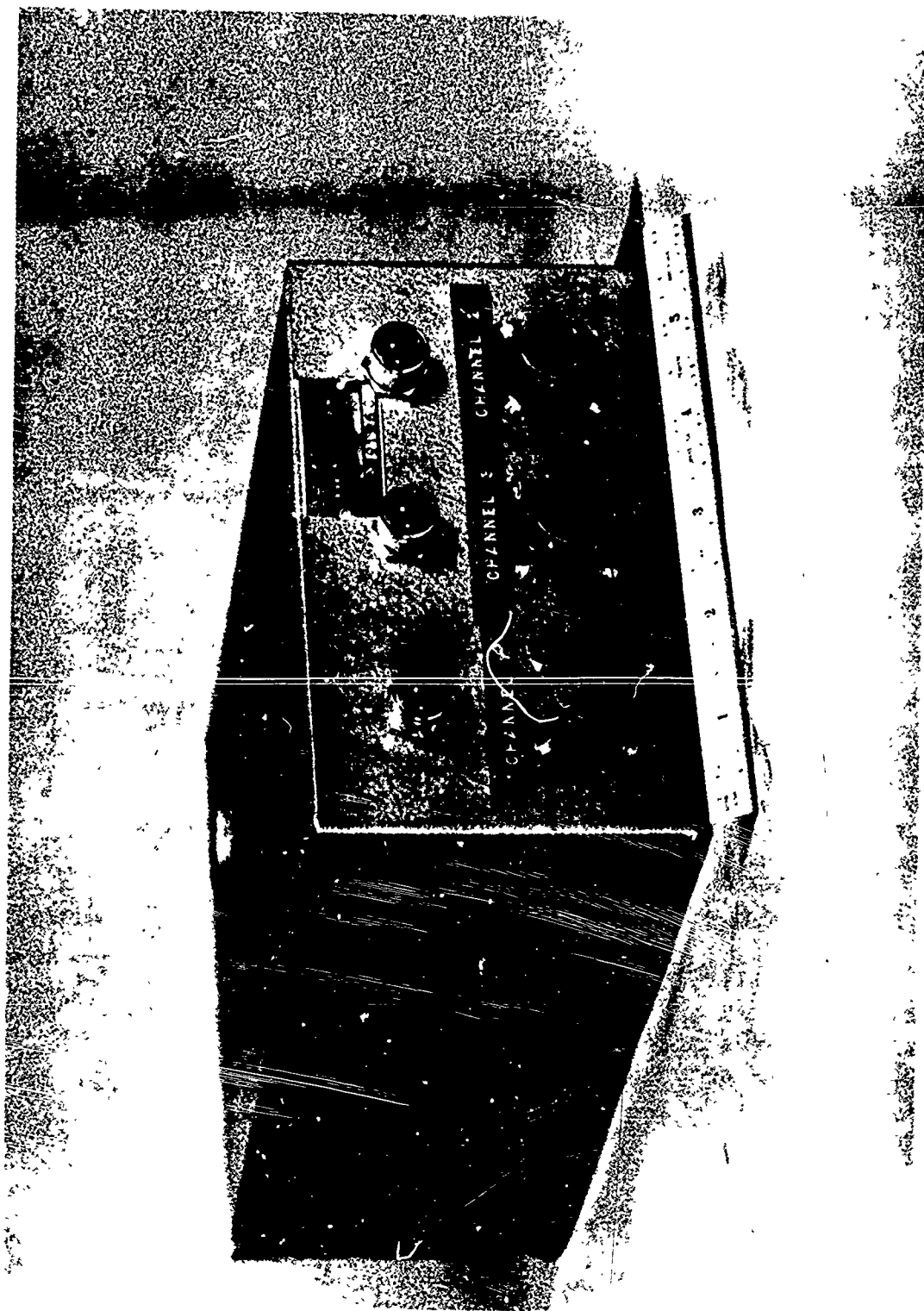
Figure 77. Failure Detection Monitor

two. Dynamic differences are tolerated by a monitor error
integrating time constant of 0.2 to 0.5 seconds.

Upon detection of a variation, the monitor disables
the failed channel by interrupting the 28 VDC electrical
power to the servovalve hydraulic supply shut off valve.
The failed channel is "locked out" to prevent random
hunting in the event of an intermittent failure. The
monitor disables itself after the first failure by lock-
ing on the remaining two good control channel servovalve
hydraulic supplies irregardless of subsequent innerchan-
nel variances.

The first failure will cause very little change in
the output of the servoactuator because the voter mech-
ansim still has two active inputs which may be voted with
the neutralized channel. However, a nonsynchronous voter
action must preside in this condition. Two active voter
inputs must continually and bilaterally move to a posi-
tion where the torque loading of the inactivated channel
is effectively cancelled, and the remaining voter input
may assume control of the servoactuator slide valve.

The second failure will cause a near complete loss
of control due to the inability of the voter mechanism
to function effectively with two neutralized inputs.
The severity of the effect of the second active control
channel failure will vary as a function of the type of
failure as discussed in reference 3.

4.4   Test Schedule

The following test schedule was developed to evalu-
ate the dynamic performance characteristics of the McDon-
nell Douglas single fail operate FBW system in the vari-
ous possible modes of operation and with certain select
simulated failures.

      a. Determine the unloaded nominal
          dynamic response characteristics
          in the single fail operate mode.

      b. Determine the loaded nominal dy-
          namic response characteristics

114

in the single fail operate mode.

c. Determine the unloaded dynamic
response characteristics with a
failure of one of the three ac-
tive control channels. Fail-
ures are to be simulated by in-
terrupting the 28 VDC power to
the selected control channels.

d. Determine the unloaded dynamic
response characteristics with a
single hardover failure applied
to one of the three active con-
trol channels. Evaluate for
both positive and negative pc-
larities of the hardover sig-
nal.

e. Determine the failure detection
characteristics of each active
channel with a 3 H_z sinusoidal
input. Evaluate with hardover
failures of both positive and
negative polarity.

4.5 Test Procedure

4.5.1 Single Fail Operate Dynamic Response Characteristics

The dynamic response characteristics were evaluated
by determining the amplitude degradation and phase shift
of the actuator output over a frequency range of 0.1 to
20 H_z.

The pilot input feel system was disconnected and the
control linkage was driven with a sinisodial output motion

115

from a closed loop electrohydraulic servomechanism assembled specifically for this purpose.

The servoactuator was designed and bricated by Hydraulic Research and Manufacturing perst el for application as the output actuator for the B-47 phase one and two flight test evaluation disclosed in Volume II of this report.

The servoactuator drove a linkage attached to the control column pivot shaft. Position feedback was provided by a DC biased potentiometer attached at the end of the control column pivot shaft.

The servovalve of the servoactuator was driven from a specially constructed current amplifier and the loop gains were adjusted for a nominal first order response of 7 H_z at the -3db break point.

The servoactuator, servoamplifier and bias supplies are shown mounted on the McDonnell Douglas test bed in Fig. 78.

The input to the servoamplifier was adjusted to maintain a constant control input amplitude as the operating frequency was swept through the desired range.

The amplitude degradation of the McDonnell Douglas FBW system output actuator was referenced to a zero db point defined as 5% of the input signal that would cause a distorted output at a frequency of 3 H_z.

The demodulated output of the channel one actuator LVDT position feedback signal was obtained from a test point inserted at the input to the actuator position feedback gain resistor which terminated at the summing junction of the voltage amplifier.

The 800 H_z demodulated signal was filtered with a second order lag network having a break frequency of 80 H_z. The filter break frequency was designed to be approximately one order of magnitude above the expected dynamic response of the McDonnell Douglas FBW system.

The filter output signal was coupled to the horizontal

116
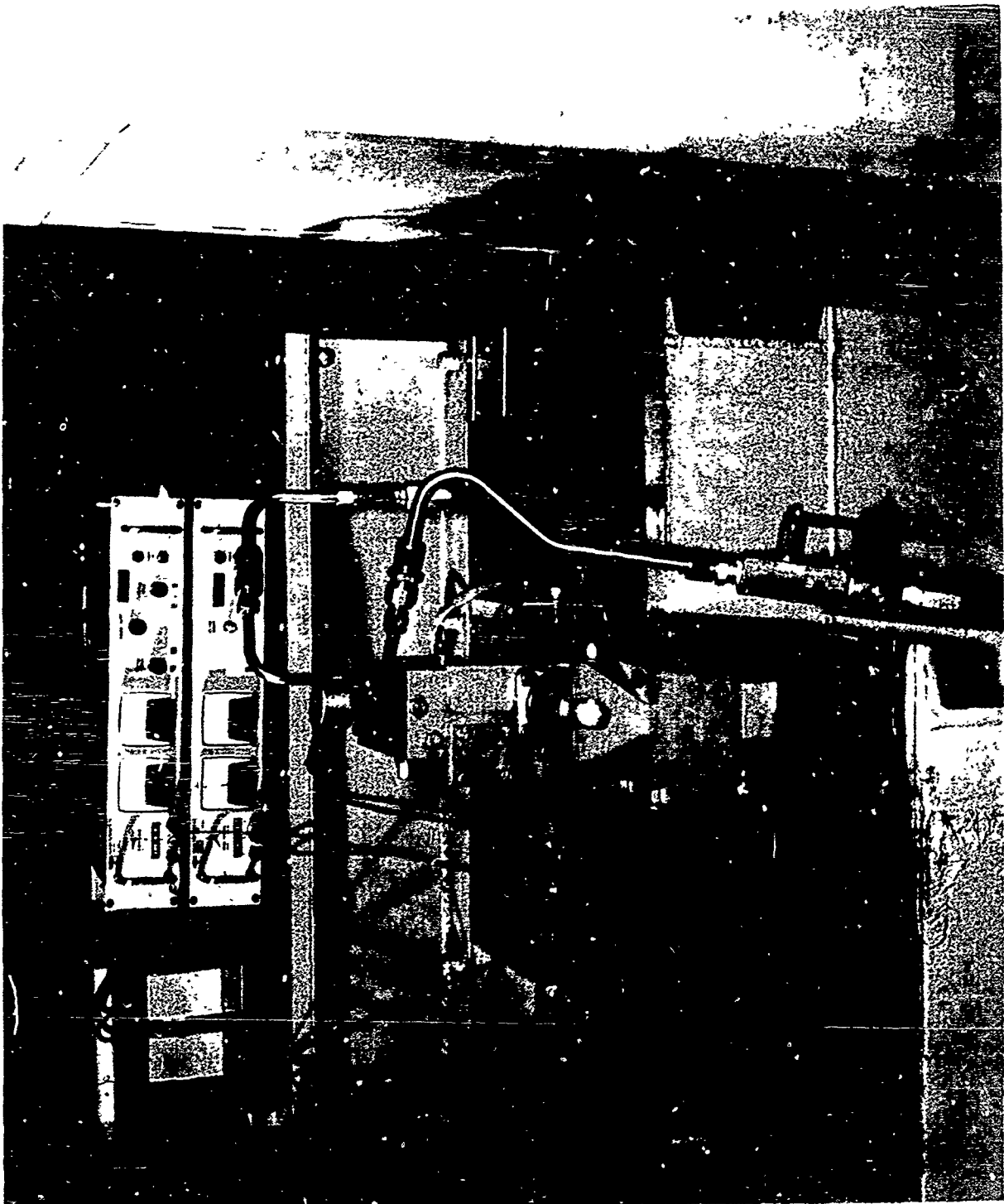
Figure 78. Electrohydraulic Servoactuator Input Mechanism

117

ysis of a DC coupled oscilloscope. The amplitude decay
of the actuator output was determined by monitoring the
degradation in the filter output signal as the control
channel input was swept over a frequency range of 0.1
to 20 Hz.

The relative phase shift of the filter output sig-
nal was observed by the use of the Lissajous pattern tech-
nique.

The control column input signal was obtained from
the feedback potentiometer of the servomechanism assem-
bled to drive the McDonnell Douglas FBW system. This
signal and the filtered output signal from the channel
one McDonnell Douglas FBW servoactuator demodulated were
applied to the axes of a DC coupled oscilloscope to ob-
tain the Lissajous pattern for phase shift measurements.

The unloaded dynamic response evaluations were made
by removing a portion of the linkage that connected the
output actuator to the attached load.

4.5.2   Failure Detection Characteristics (4.4 e)

The McDonnell Douglas FBW system was driven at 3 H_z.
The servoactuator demodulated and filtered output signal
was monitored with an oscilloscope and Polaroid camera
attachment. Positive and negative hardover signals were
injected into each channel and the resulting deviations
in the waveform of the motion of the servoactuator were
recorded on film.

4.6   Test Result and Analysis

4.6.1   Initial Operational Problems

The McDonnell Douglas FBW system would not operate
with all channels engaged when the evaluation was initia-
ted. The problem was traced to a gross mismatch in the
DC null of the servoamplifiers which was causing the moni-
tor to disable channel two on a continuous basis. The
servoamplifiers were electrically nulled by adjusting the
potentiometer provided for this purpose through a small

hole in the servoamplifier case that was obviously placed to facilitate this operation. The null characteristics were found to drift very badly. The control channels required a 24 hour warm-up period to stabilize the output.

The McDonnell Douglas FBW system was then operated with manual inputs to the control stick and it was discovered that any input greater than that sufficient to cause a $\pm 1^o$ movement of the control surface would cause the monitor to consistently disable channel two.

This problem was initially traced to a mismatch in the open circuit amplitude of the signals from each triple tandem LVDT transducer assembly. The channel electronic modules were inspected and found to contain 10 turn linear potentiometers inserted as voltage dividers at the output terminals of each LVDT demodulator.

The signal amplitude of each output of each triple tandem LVDT assembly, including the control stick input unit was then painstakingly matched on a dynamic basis by adjusting the potentiometers provided for this purpose. During the completion of this procedure, it was discovered that the channel two servoamplifier was displaying an unusual diode characteristic in that the amplifier gain varied as a function of the amplitude of the input signal. The amplifier was replaced with a similar unit from the spare electronics module supplied with the FBW system and the variable gain characteristic was eliminated.

The McDonnell Douglas FBW system was then reactivated and found to function satisfactorily at signal inputs that would not cause a surface deflection in excess of two degrees at 1.0 H_z. Above this level, the monitor continued to disable channels on an indiscriminate basis and was finally bypassed for the remainder of the evaluation with the override switch provided for this purpose.

The unloaded dynamic response of the McDonnell Douglas FBW system was evaluated and found to be 4 H_z at the -3db break point. This was a considerable deviation from

119

the response measurements shown in the system test results
of reference one and a decision was made to attempt to
adjust the loop gains for maximum dynamic response with-
out instability.

The loop gains were adjusted on a trial and error
basis by increasing the outer loop gain in small matched
movements and noting the change in the nominal dynamic
response characteristics. The final result was that the
dynamic response characteristics were significantly im-
proved. The system did become unstable at very high outer
loop gain settings, but the inner loop gains for the mo-
dulating piston and slide valve feedback were adjusted
to eliminate this instability.

The McDonnell Douglas FBW system was then powered
up and allowed to stabilize for several days after which
a final DC null trim adjustment was performed prior to
initiation of the evaluation tests.

4.6.2 Dynamic Response Evaluation

The results of the evaluation of the dynamic res-
ponse of the McDonnell Douglas FBW system in the single
fail operate mode are shown in Fig. 79 through 82. In
general the dynamic response characteristics remain con-
sistent throughout the investigated modes of operation.
The response characteristics illustrate a significant pre-
dominance of higher order effects. The system bandwidth
remains very flat out to a well defined "porch" followed
by a near linear decay in the amplitude ratio of approxi-
mately 9 db per octave.

The frequency response of the McDonnell Douglas
FBW system in all investigated modes of operation varied
from 8 to 9.5 H_z at the -3db break point,

The phase shift characteristics show a sudden, very
large increase in the relative phase shift in the fre-
quency region of 6 - 9 H_z which correlates with the de-
gradation in the amplitude ratio previously observed.

The unloaded and loaded dynamic response charac-
teristics, Fig. 79 and 80 show that the application

120
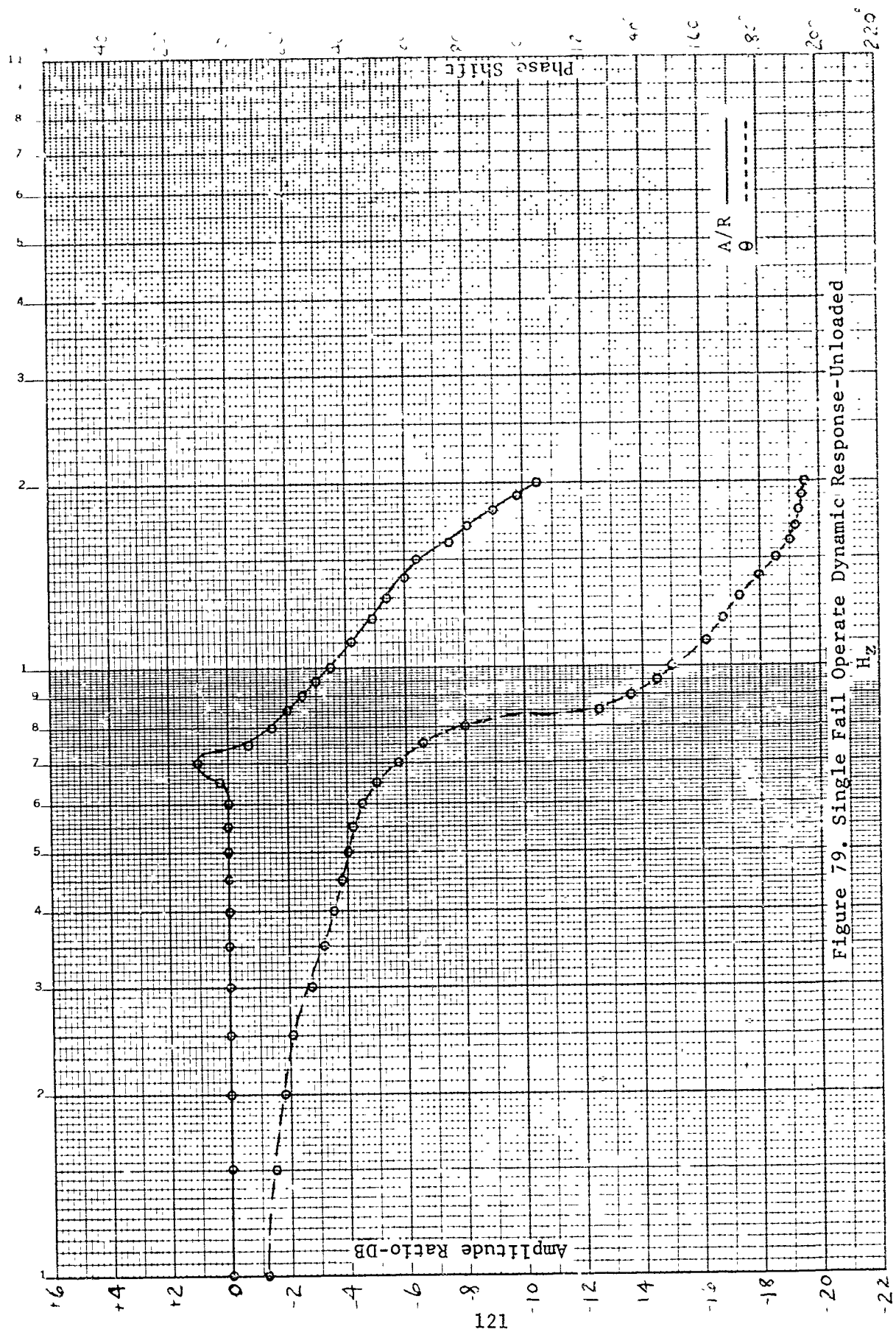
Figure 79. Single Fail Operate Dynamic Response-Unloaded

121
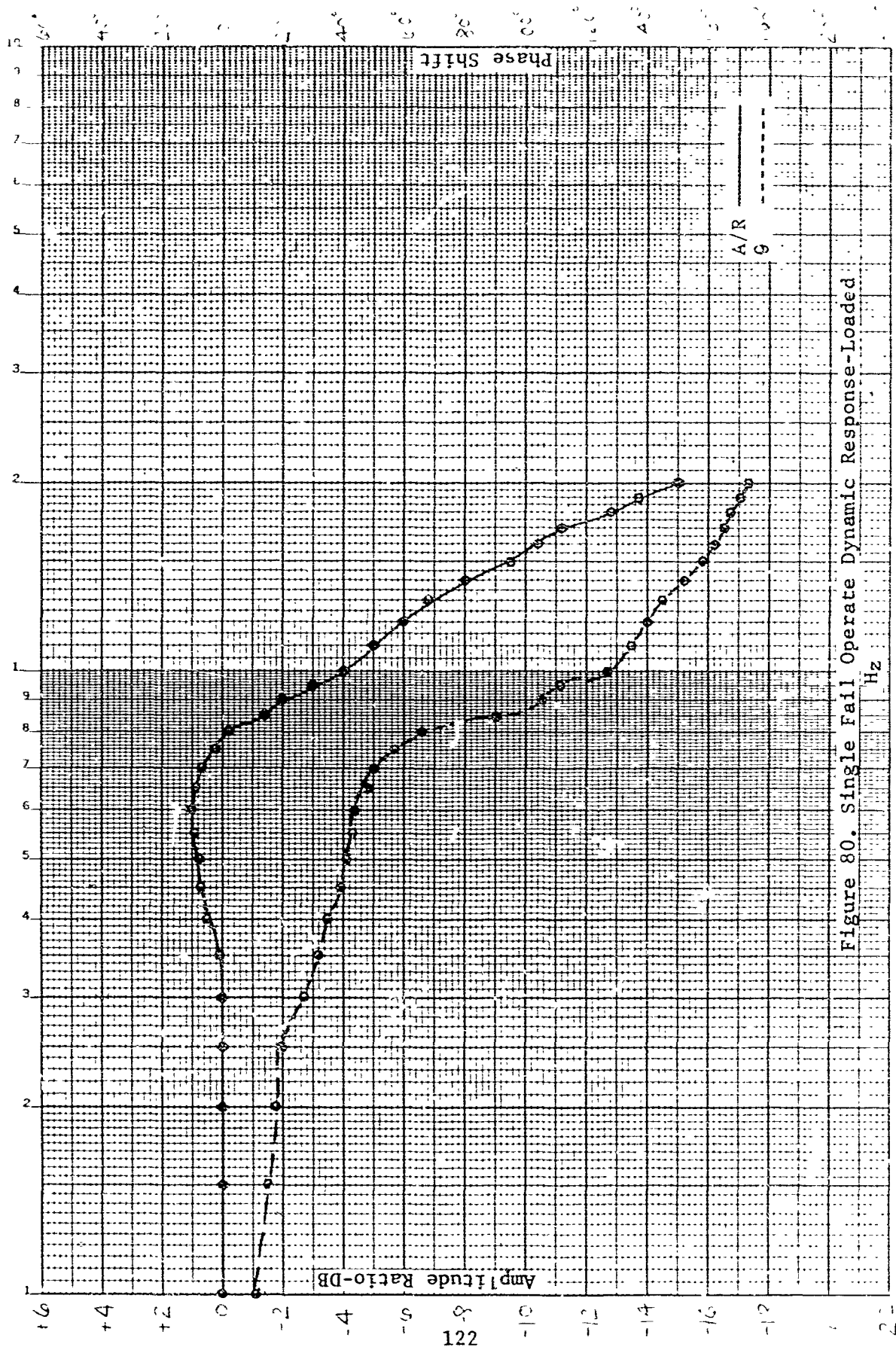
Figure 80. Single Fail Operate Dynamic Response-Loaded
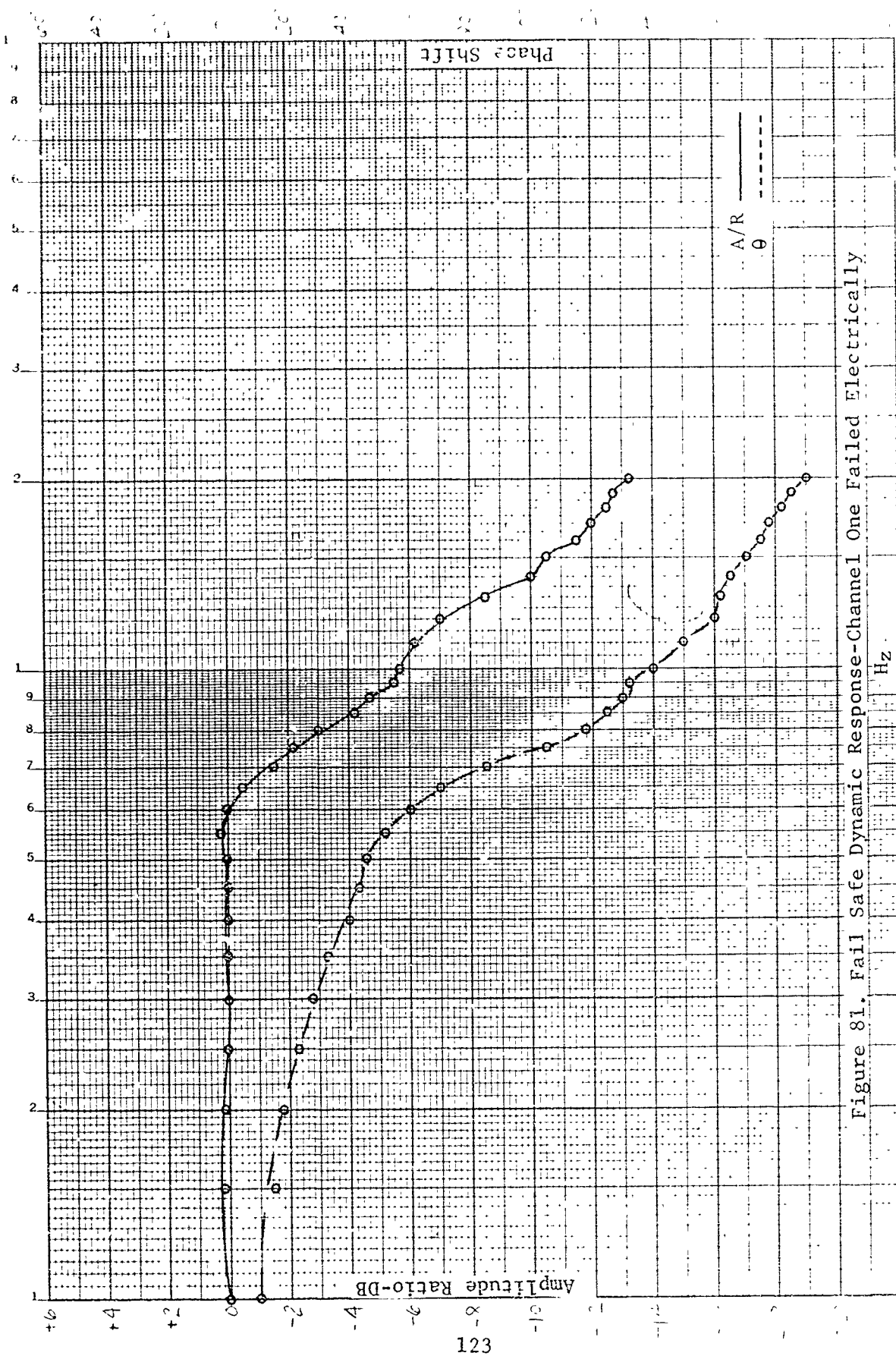
Figure 81. Fail Safe Dynamic Response-Channel One Failed Electrically.

123
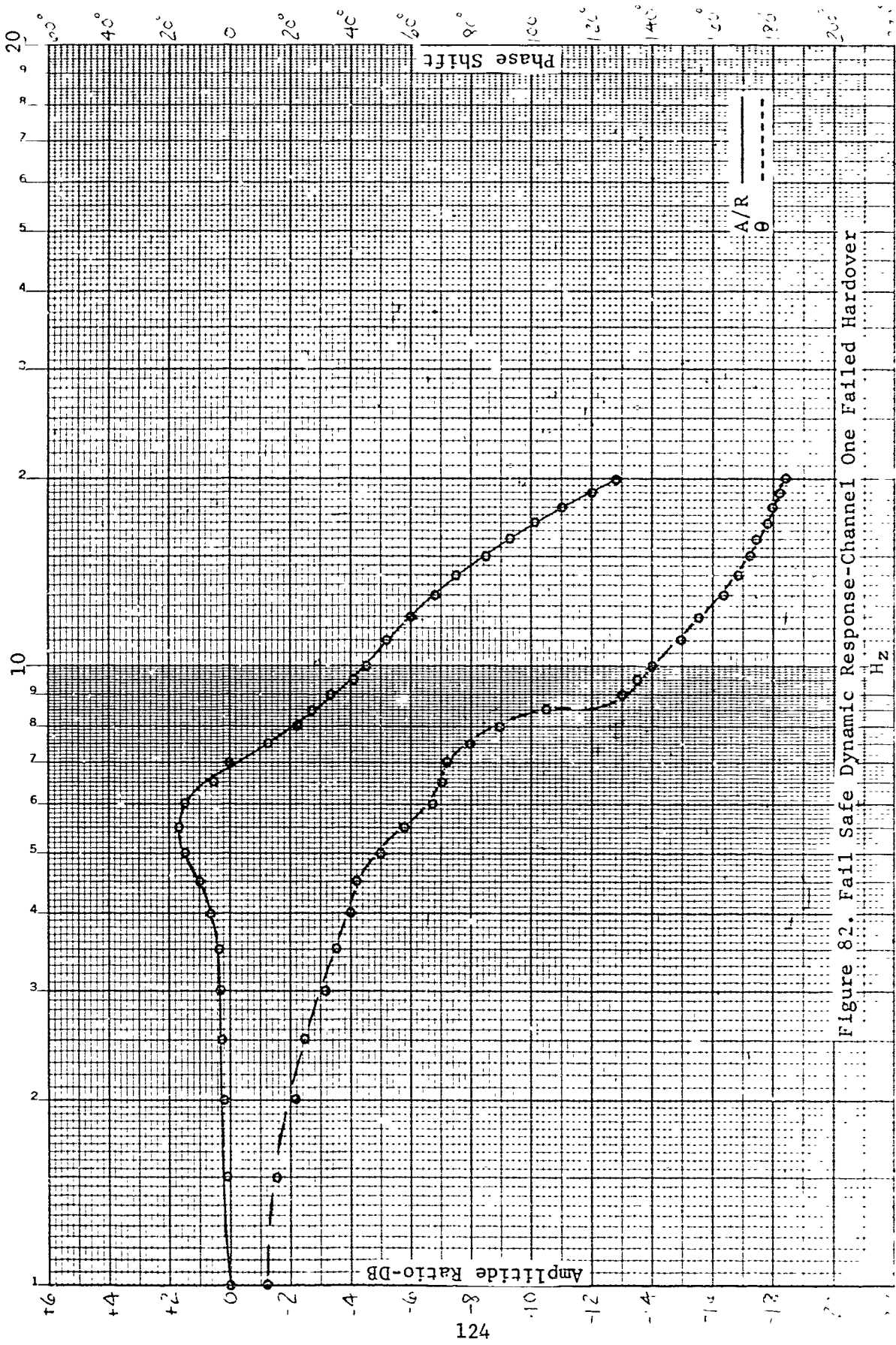
Figure 82. Fail Safe Dynamic Response-Channel One Failed Hardover

124

of simulated aerodynamic loads has very little effect
on the performance characteristics of the system.

The dynamic response characteristics of the Mc-
Donnell Douglas FBW system in the unloaded mode with
simulated failures is shown in Fig. 81 and 82. Single
failures of the active or passive type did not materi-
ally affect the performance characteristics of the FBW
system.

4.6.3 Failure Detection Characteristics (Monitor De-activated)

In normal operation, the system monitor would de-
tect hardover failures and deactivate the deviating
channel. The modulating piston would assume a neutral
position which might alter the results presented in the
following section of this report.

The instantaneous deviations in the 3 H_z sinusoi-
dal output motion of the servoactuator with hardover
failures injected one at a time into each active chan-
nel are shown in Fig. 83 through 85. In general the
results illustrate that the voter mechanism effectively
decouples the hardover inputs with very little distor-
tion of the servoactuator output waveform.

The channel one results shown in Fig. 83 show the
maximum actuator output waveform deviation experienced
in this evaluation. The results indicate that channel
one voter arm was in control of the voter output shaft
and actuator slide valve when the hardover input was
injected. The voter mechanism assumed a new position
of torque equilibrium which produced an actuator posi-
tion offset equal to 0.50° of surface deflection. The
offset was in the direction of the hardover input.

The channel two and three test results show little if
any effect as a result of the injection of a hardover signal.

4.7 Conclusions

The bandwidth of the refurbished McDonnell Douglas
FBW system is very adequate for fly-by-wire applications.

125

Hardover Positive

Hardover Negetive

Vertical 1^O Surface Motion / Major Div.
Horizontial   0.16 Sec/ Cm.

Figure 83. Channel One Failure Detection Characteristics

126
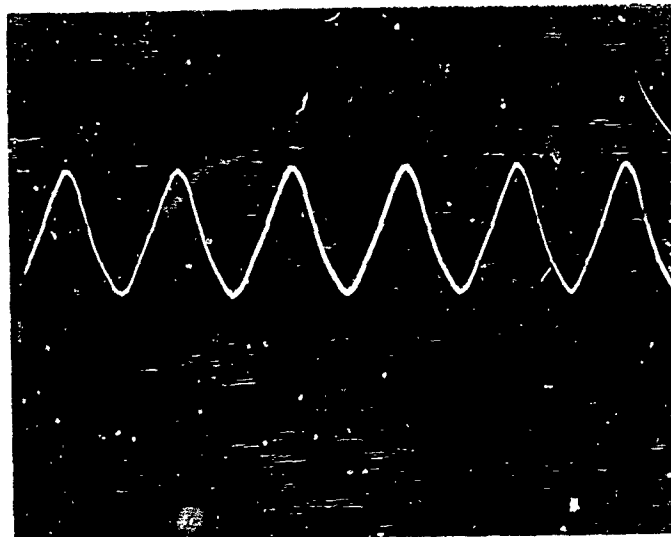
Hardover Positive

No Measureable Effect

Hardover Negative

Vertical 1° Surface Motion / Major Div.
Horizontial   0.16 Sec/ Cm.

Figure 84. Channel Two Failure Detection Characteristics
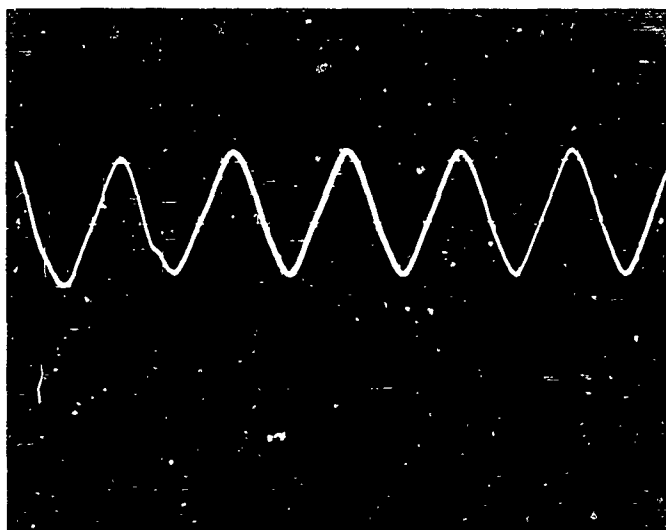
Hardover Positive
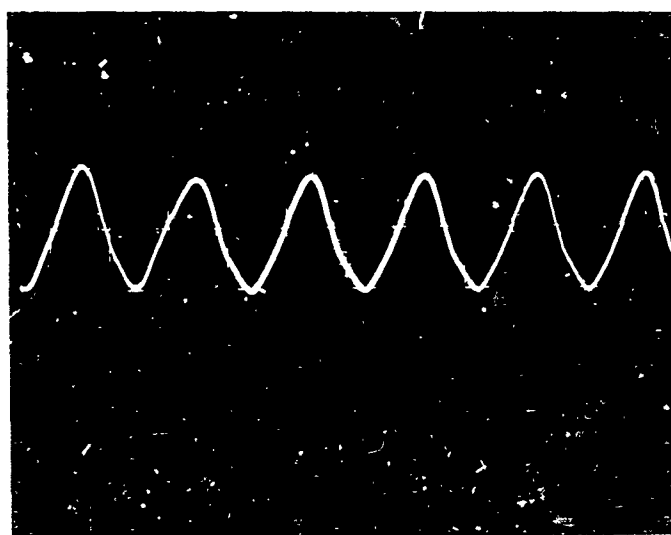
Hardover Negetive

Vertical   1° Surface Motion / Major Div.
Horizontial   0.16 Sec/ Cm.

Figure 85. Channel Three Failure Detection Characteristics

128

The voter mechanism functions very well in de-
coupling active or passive control channel failures in
the single fail operate mechanism. However, the prin-
ciple could not be applied to a two fail operate mech-
anization unless the additional active channel input
to the voter torque summation shaft is decoupled until
the first failure is detected and removed.

This requirement is necessitated by the fact that
a median select system cannot function with four inputs
because there will be two mid-values.

The control channel electronic hardware is of
marginal quality and definitely not adequate for fly-by-
wire applications. The operational amplifiers are not
stable and exhibit a gross long term drift characteris-
tic which can only be corrected by the complete replace-
ment of the entire servoamplifier network with state of
the art chopper stabilized devices which have very fav-
orable and very long term limited drift characteristics.

In addition, the hydraulic supply solenoid valves
are not of the continuous duty type, although the method
of operation of the FBW system requires this specifica-
tion. Consequently, two of the three solenoid valve
electromagnets shorted during the evaluation. The first
short caused extensive damage to the internal wiring in
the control console as a result of the use of low tem-
perature thermoplastic sheaths and the commonly applied
practice of running power and instrumentation wiring in
a common laced bundle.

The solenoid short caused excessive current in the
DC power conductors to the valve and the switches on the
control console. The solenoid DC supply was not wired
through a fuse, although several spare fuse elements
were provided on the control console. Therefore, the
current surge melted together several cable assemblies
before the power could be manually interrupted at an
external circuit breaker.

This instance and others of a like nature discus-
sed in this report that have occurred in the performance
of this contract indicate the dependency a fly-by-wire

129

system placed on the integrity and quality of the inter-
connecting wir·ng and the craftsmanship of the fabrica-
tors and installers of fly-by-wire systems.

4.7   Recommendations

The McDonnell Douglas fly-by-wire laboratory model
demonstrator performance characteristics are totally
dependent upon the integrity of the voter mechanism.
This device is purely mechanical and is thus subject to
wear as a result of the continuous movement of the voter
input arms and output shaft. In addition, the voter mech-
anism may be sensitive to forcing functions caused by
acceleration and vibration inputs.

Therefore, it is recommended that a wear life and
environmental test evaluation be conducted on this sen-
sitive area. The McDonnell Douglas FBW system should
be run on a continuous cyclic basis and the dynamic res-
ponse and failure detection characteristics should be
evaluated on a scheduled basis with and without envir-
onmental effects, to determine if the voter mechanism
performance will degrade with continued use.

In addition, the monitor device should be refur-
bished and the failure detection characteristics should
be re-evaluated with the monitor functioning. The de-
tection characteristics may be changed by the fact that
the monitor disables the hydraulic supply to the servo-
valves thus neutralizing the respective channel modu-
lating piston. The failed channel voter arm may cause
more interference in the position because it will lag
very near the zero center position of the voter output
shaft and may introduce crossover distortion as the sys-
tem input swings through the slide valve center position.

REDUNDANT ACTUATION AND CONTROL
EQUIPMENT DESIGN TECHNIQUES

1. TECHNICAL APPROACH

In the last ten year period, there has been considerable
activity in the field of redundant flight control systems.
This has been particularly true in the area of redundant elec-
trohydraulic control systems based on using electrical rather
than mechanical transmission of control signals. To meet the
reliability demands on the electrical "fly-by-wire" control
systems, various redundancy techniques for the electrical
and electrohydraulic elements have been developed. Some of
the current techniques carried through to flight equipment
exist in the F-111, Concord SST, TWeaD F4 (experimental) and
Triple Six F4 (experimental).

The redundancy technique most commonly used to improve
the reliability of the electrical elements is based on a
median select mechanization. This mechanization connects
the output of the redundancy block to the element whose out-
put lies between the other two elements, both in amplitude
and polarity. In the case of electrohydraulic actuator re-
dundancy, the techniques used to incorporate redundancy vary
from force-sharing to active-standby mechanizations. The
force-sharing mechanization couples the outputs of three
or more control elements together so that the deviations of
any one element tend to be cancelled out by the other paral-
lel elements. In the active-standby system, each control
element's performance is monitored and the control elements
are selectively coupled to the output of the mechanization.
Only one control element is coupled at any one time to the
output.

Application of the force-sharing mechanization is con-
fined to "series"-type actuators. (A series actuator is
considered to be one that is in series with the control in-
put, and normally drives the input linkage of an actuator
driving a control surface.) The high actuator stiffness
required to drive a control surface makes the force-sharing
technique (with its required parallel element force output
matching) too difficult to be practicable at that point in
the control system. The active-standby mechanization is

131

utilized both for series and surface type actuators.

All of the redundancy techniques to date have based their design on the use of parallel control elements in order to improve reliability. All of the redundancy techniques also incorporate some "common" elements. (A "common" element is one whose operation affects the total input-output operation of the redundancy block.) These common elements appear in the monitoring and switching elements of the active-standby mechanizations. In the force-sharing and median select mechanizations, the common elements appear in the connection of the output of the redundancy elements into one common electrical or mechanical item.

From the standpoint of the reliability achievable from parallel-element redundancy, there is a significant advantage in eliminating all common tie points between redundant control channels in a redundant control system mechanization. This includes eliminating the elements used to make comparison between control channels for the purpose of failure detection as well as the output common element.

This principle is recognized in some of the latest aircraft designs, even with some of the conventional control system mechanizations. Some of the large aircraft now employ split surfaces. Even in the split surface configurations (basically an aerodynamic force sharing mechanization) it is necessary to monitor the individual failures. The input-output monitoring technique does not solve the problems of surface synchronization, but does maintain interchannel isolation of the monitoring elements and detects channel failures.

The theoretical basis for this approach can be seen by examining the reliability diagrams and expressions for a general parallel-redundancy mechanization. The analysis is based on the following points.

    1. In a redundant system, component failures have only the two following effects on the system:

        a) The component failure appears as a single channel failure, and

        b) The component failure fails the function of the whole system.

2. The function of the redundant control system is twofold:

    a) The system generates an output in relation to some input, and
    b) In the event of a component failure, the mechanization detects the failure and removes its effect on the output of the system.

Therefore, by categorizing, as listed above, the failures of the elements making up a redundancy mechanization, component reliabilities can be represented as either <u>series</u> or <u>parallel reliabilities</u> in a reliability flow diagram.

Consider a 3-channel redundant system. In the following general reliability flow diagram, R_1, R_2, and R_3 are the reliabilities of those control elements appearing as channel failures, while R* is the reliability of those elements whose failures would cause total loss of the system function.
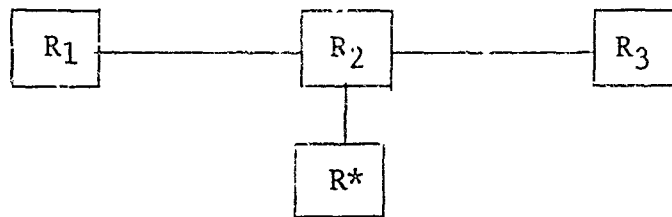
Assume that $R_1 = R_2 = R_3$, and that any one of the three parallel units being operational is adequate for the operation of the redundant configuration. The reliability of the three parallel element configuration is:

$$R_s = R^* (1 - Q_1^3)$$ where R is the probability of no failure,

Q is the probability of failure,

$R + Q = 1$, and

R_s is the system reliability.

It is interesting to examine the above reliability equation, assuming that the series reliability R* is <u>100 times as</u>

reliable as R_1. This means that $R* = 1 - 0.01 Q_1$

$$\text{Therefore } R_s = (1 - 0.01Q_1)(1 - Q_1^3)$$

$$R_s = 1 - 0.01Q_1 - Q_1^3 + 0.01 Q_1^4$$

Calculating R_s, the system reliability, and the reliability of the parallel elements without R*; and with R_1 varied:

> (Reminder: the series element reliability in all cases is 100 times better than that of a single parallel element.)

	R_1	R_s	Parallel Elements Alone $(1 - Q_1^3)$
Case I	0.9	0.998	0.999
Case II	0.99	0.9999	0.999999
Case III	0.999	0.99999	0.999999999
Case IV	0.9999	0.999999	0.999999999999

The reliability difference (without the series element R*, as compared to with it) is:

> Case I is 2 to 1
> Case II is 100 to 1
> Case III is 10,000 to 1
> Case IV is 1,000,000 to 1.

What is indicated, as the reliability of parallel elements is improved through design evolution or technological breakthrough, is that the benefits of redundancy are dramatic if the series or "common" elements can be eliminated. What is also indicated is that pure parallel redundancy has the potential of allowing control system reliability equal to that of the airframe itself.

134

It therefore appears that the primary objective of the design of any redundancy mechanization should be the elimination of "common" elements. While total elimination is probably not practical with current state-of-the-art control techniques, selection of allowable common elements should be very carefully done, in order to realize even some of the reliability improvement possible with parallel element redundancy.

SECTION IV

INVESTIGATION OF POWER SWITCHING VALVES

1. INTRODUCTION

In incorporating redundancy in flight control system, it is sometimes desireable to switch hydraulic supplies to a hydraulic branch, when the normal hydraulic supply fails. To investigate the feasibility of such a switching device, a power supply switching valve was designed, fabricated and laboratory tested. The valve, upon the reduction of the primary supply pressure to 1/3 of the secondary supply pressure, transferred both supply and return line output connections to the secondary hydraulic system.

2. MECHANIZATION DESCRIPTION

Fig. 86 is a cross-section drawing of the valve. In order to minimize contamination sensitivity, no lapped fit seals were used to seal off the supply pressures. Metal to metal cone face seals were used to block the two supply pressures. To prevent flow (which could cause silting by carrying in dirt) through the clearances between the switching spool and its sleeve, teflon cap seals were used on the spool.

The principle of operation was based on a force unbalance applied to the switching spool end. As long as the primary hydraulic supply pressure remained above 33-1/3% of the secondary supply pressure, the pressure on the spool end areas generated a force which held the switching spool to the left (as shown in Fig.86), connecting the primary hydraulic system P_1 and R_1 to the output pressure and return ports. With the reduction of the primary supply pressure below 1/3 of the secondary supply pressure, the switching valve moved to the right, connecting supply P_2 and R_2. Fig.87 is a photograph of the test valve hardware.

In constructing the switching valve, the spool was fabricated from a hardened stainless steel. The portion of the sleeves containing the cone seats for pressure shutoff were fabricated from brass. This material was selected to allow the hardened shutoff spool to form its own seat. The pressure drop with flow through the switching valve was
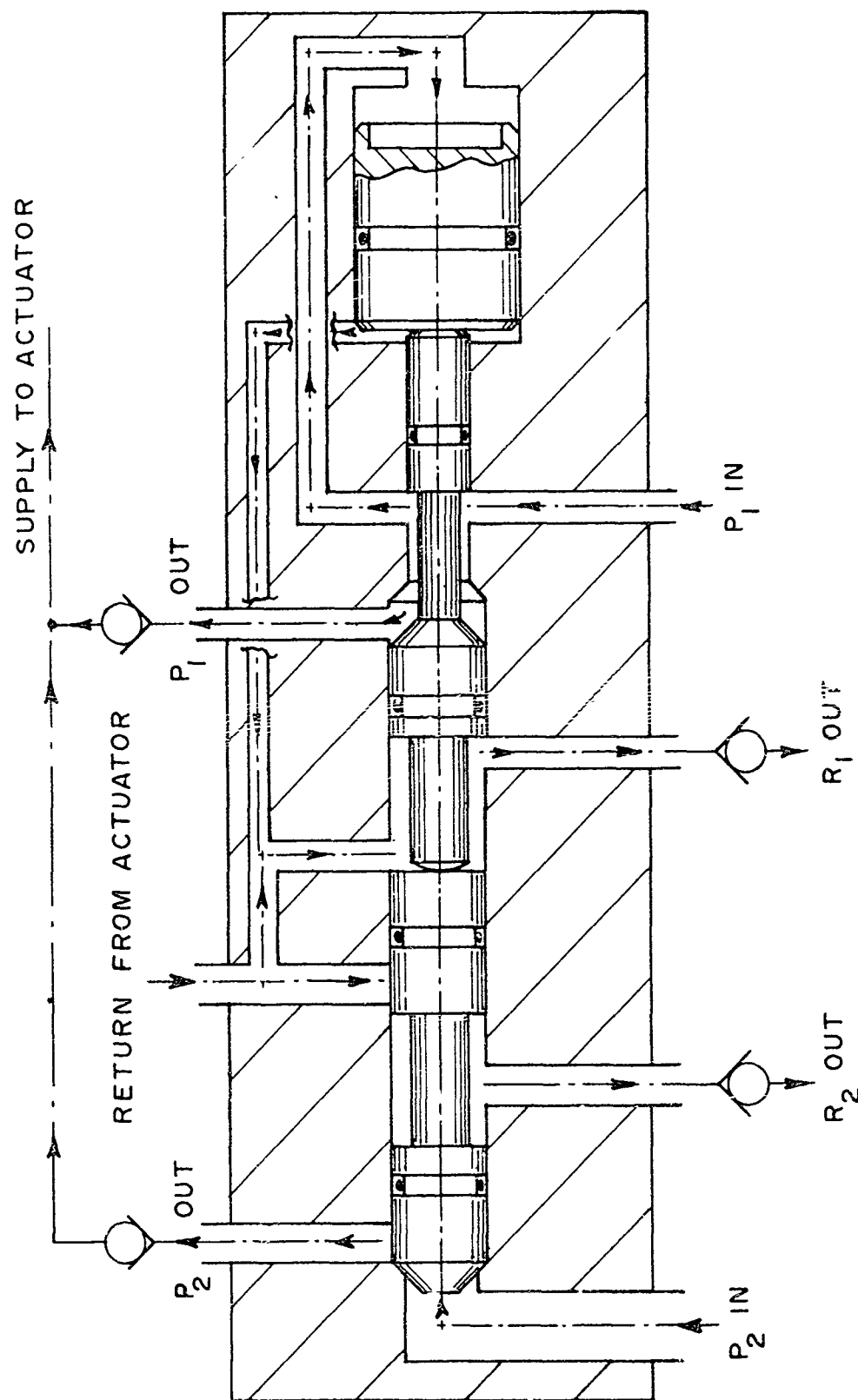
136

SUPPLY TO ACTUATOR

RETURN FROM ACTUATOR

P_1 OUT

P_1 IN

R_1 OUT

R_2 OUT

P_2 OUT

P_2 IN

137

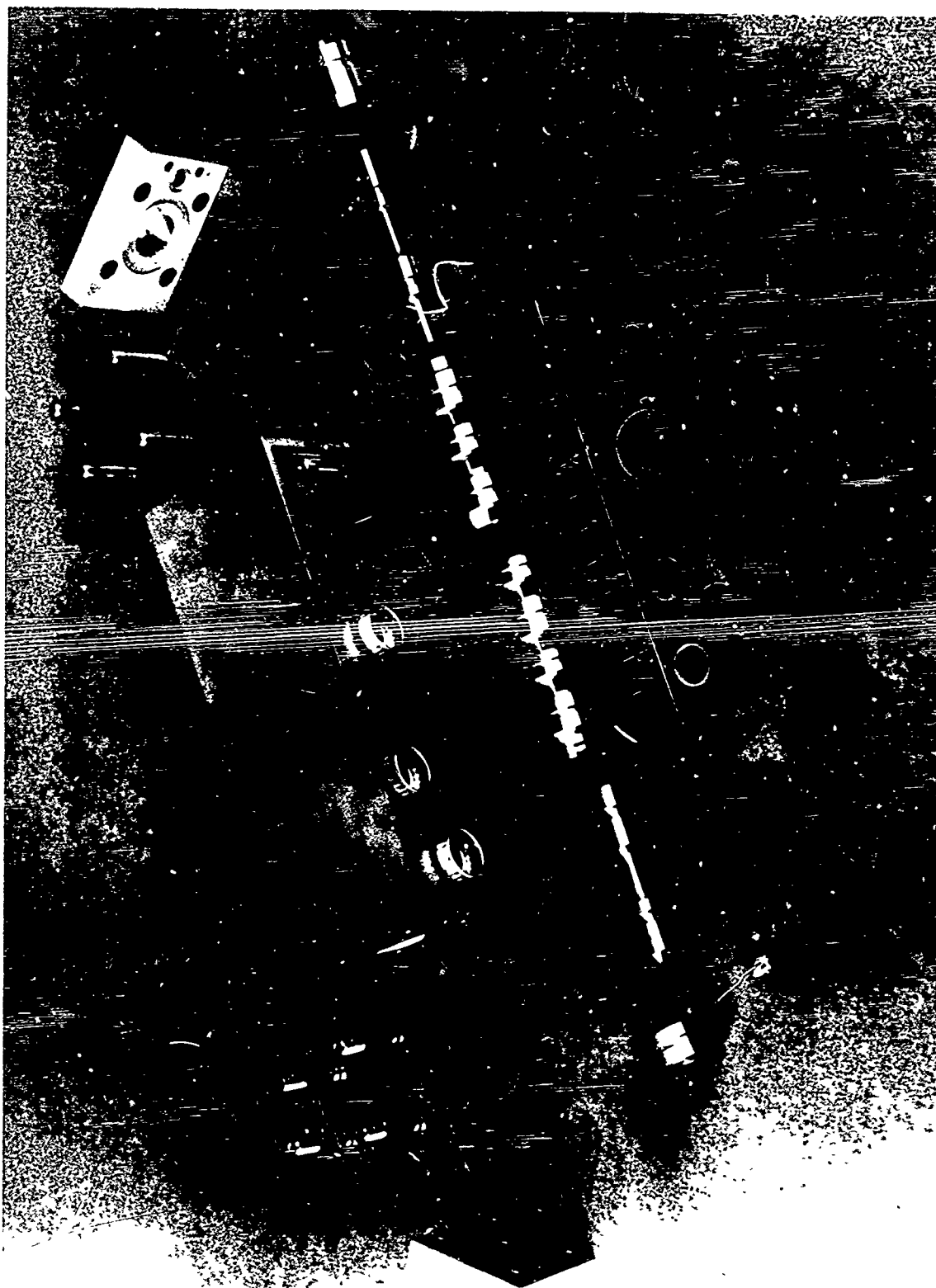Figure 86. Cross Section Drawing of Power Switching Valve

Figure 87. Test Valve Hardware

designed to be 10 psi at 20 GPM.

3. TEST PROCEDURE

The switching valve was connected in the test circuit shown in Fig. 88 . Supply pressure P_2 was maintained at 3000 psi while P_1 was lowered. The pressure gauge connected to the switching valve output pressure port was used to indicate the supply system transfer point. The load valve was used to vary the flow through the switching valve from 0 to 10 GPM, while checking the switching characteristics.

The pressure transducer and chart recorder were used to record the transfer characteristics.

4. TEST RESULTS

With P_2 at 3000 psi, the switching block transferred when P_1 was reduced to 600 psi. After transfer to the P_2 system, increasing P_1 to 900 psi caused the switching valve to reconnect the P_1 supply to the output. The difference between the 1000 psi design switching level and the measured 600 psi was due to the P_2 drive area (determined by the exact sealing point on the cone face seal) being slightly smaller than anticipated. Fig. 89 shows the measured output characteristics when P_1 system supply stand was turned off while flowing 1 GPM at 3000 psi.

5. RECOMMENDATIONS AND CONCLUSIONS

The switching valve worked as designed. The design which was tested incorporated face seals for pressure line switching. It incorporated, however, conventional spool-sleeve shutoff for the return lines. From a contamination sensitivity design point, it would be desireable to use face seals for both the supply and return line switching. Fig. 90 shows a design approach which uses face seals for both the pressure and return line transfer.
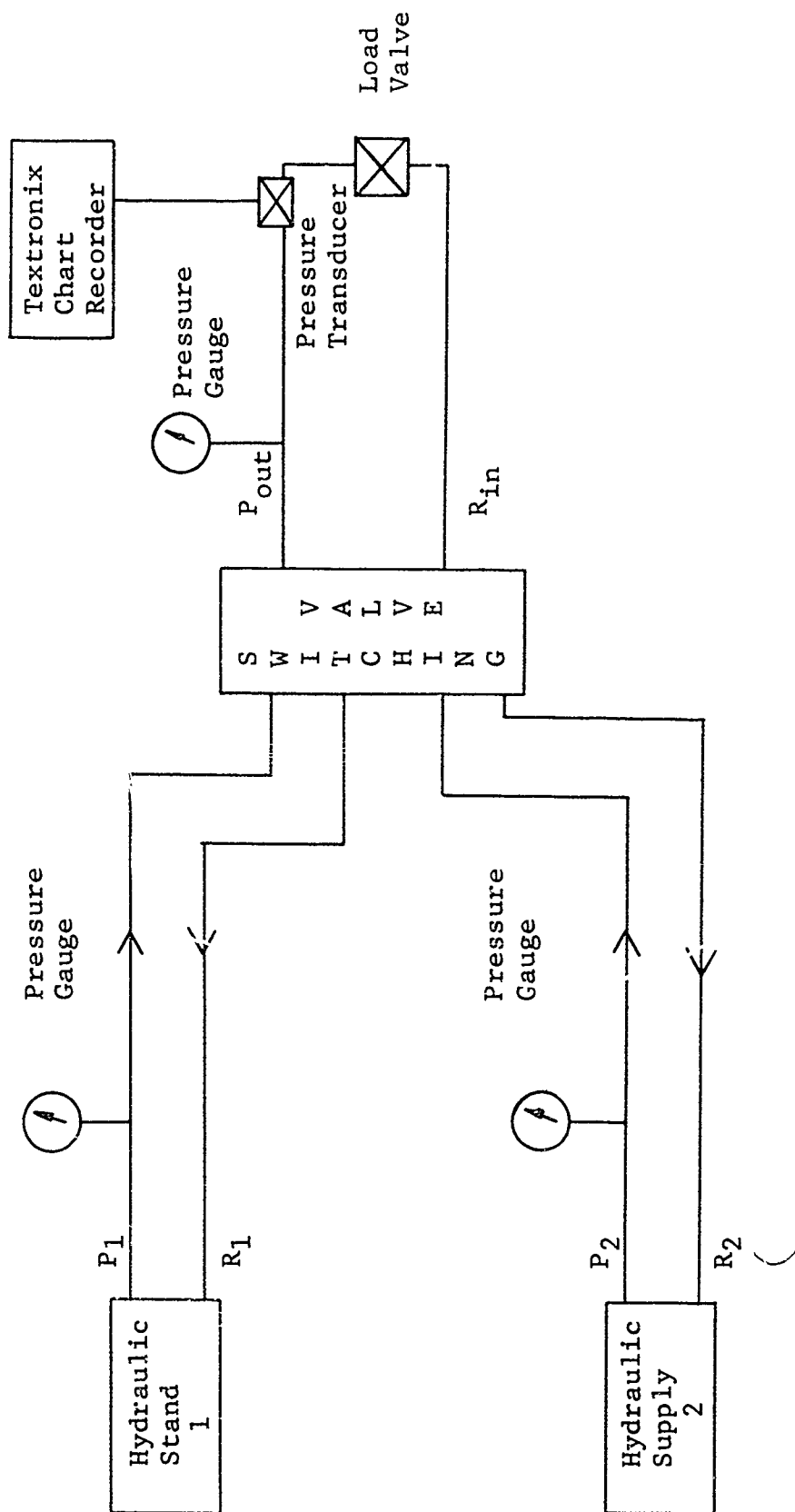
Figure 88. Switching Valve Test Circuit
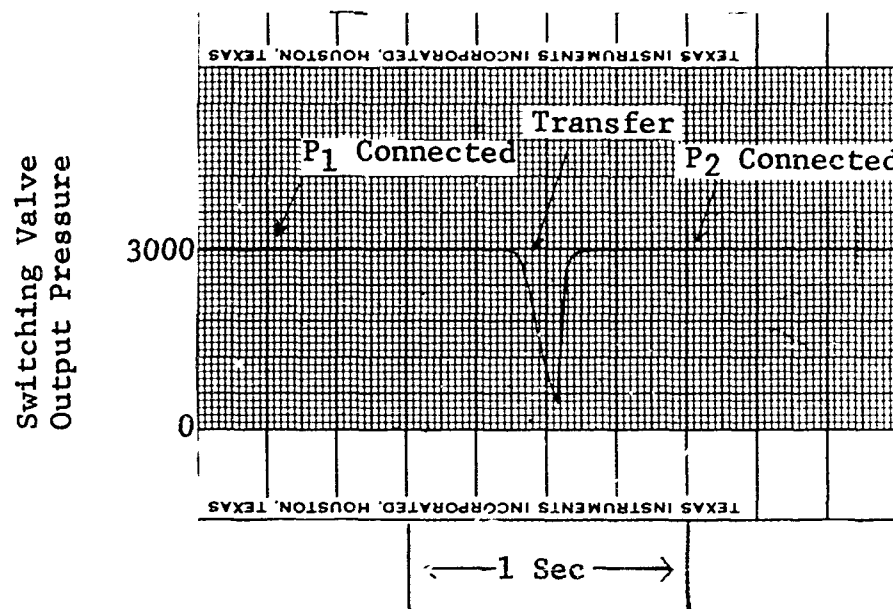
Figure 89. Power Switching Valve Transfer Characteristics

141
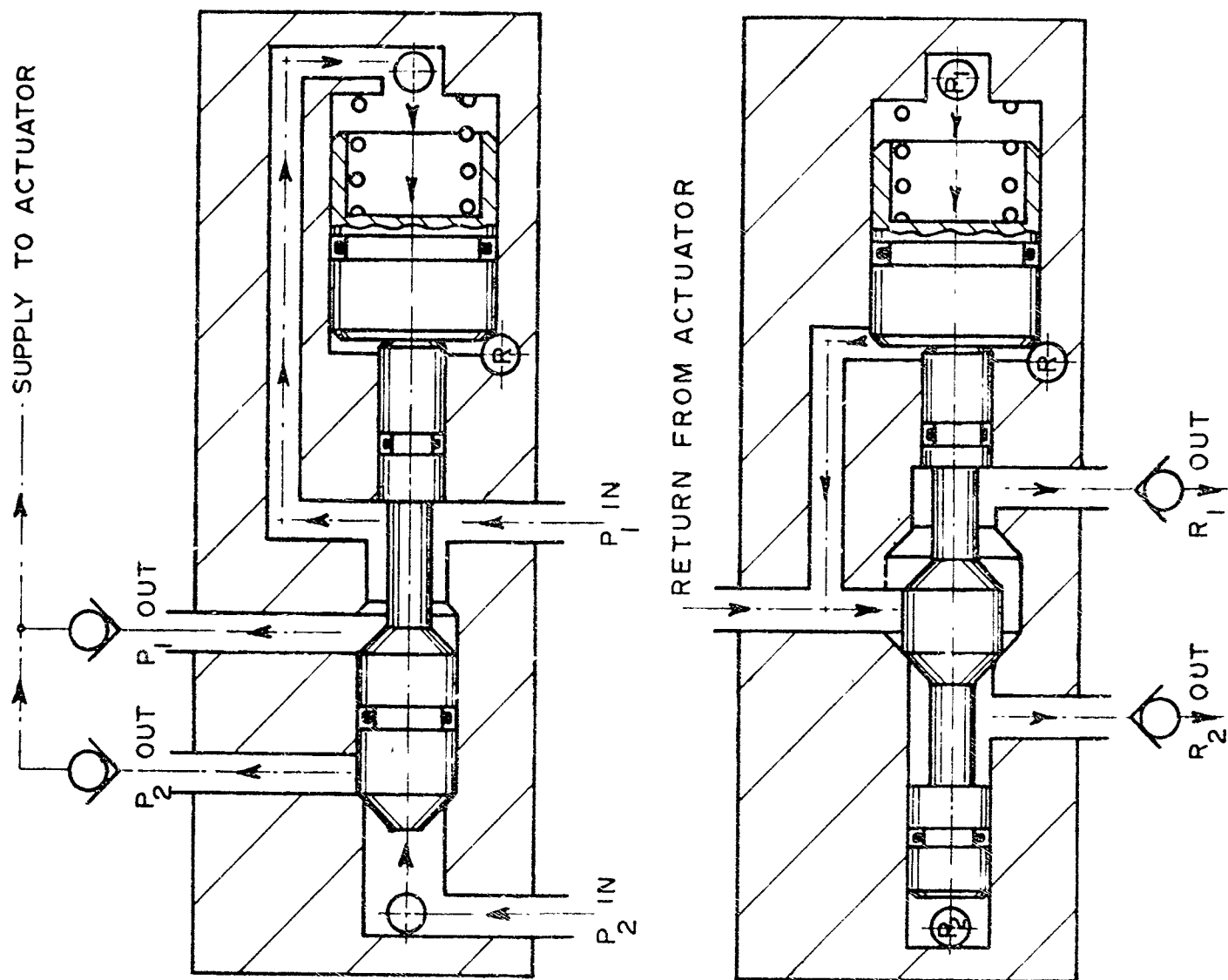
Figure 90. Power Switching Valve Design with Face Seals

REFERENCES

I   Emfinger, J.E. and Miller, F.L., Fly-By-Wire
       Techniques (Preliminary), TR-LV-1201-0723,
       Air Force Flight Dynamics Laboratory, Wright-
       Patterson Air Force Base, Ohio, February, 1967,
       Unclassified.

II   Emfinger, J.E., et. al., A Prototype Fly-By-
       Wire Flight Control System, AFFDL-TR-69-9,
       Air Force Flight Dynamics Laboratory, Air Force
       Systems Command, Wright-Patterson Air Force
       Base, Ohio, August, 1969, Unclassified.

III   Sethre, V.C., et. al., Design Techniques and
       Laboratory Development of An Electrical Pri-
       mary Flight Control System, ASD-TDR-62-46,
       Flight Control Laboratory, Wright-Patterson
       Air Force Base, Ohio, April, 1962, Unclassified.

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13 ABSTRACT   This report presents the results of an evaluation of the operational characteristics of the flight control systems and mechanizations that are permanently located in the Hydraulics Laboratory of the Control Elements Branch of the Air Force Flight Dynamics Laboratory in Building 195, Wright-Patterson Air Force Base, Dayton, Ohio. This effort was performed by Hydraulic Research and Manufacturing Company personnel under Air Force Contract F33615-68-C-1638.

The flight control systems evaluated were the Sperry three axis, two fail operate, FBW system and the McDonnell Douglas single axis single fail operate system. The mechanizations evaluated were the Hydraulic Research and Manufacturing Company Polaris integrated actuator, the Vickers Model MPEV3-044-2 motorpump, and the FDCL developed hydrologic hydraulic power switching valve. In addition, a discussion of redundant actuation and control equipment design techniques is included in section three of this volume.

The investigation disclosed that the Sperry and McDonnell Douglas FBW systems have adequate dynamic response and reasonable control transfer characteristics for near future FBW applications. However, considerable refurbishing and redesign would be necessary to qualify the mechanizations for actual flight test.

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